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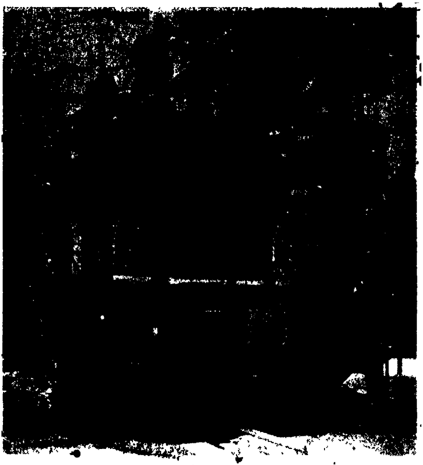

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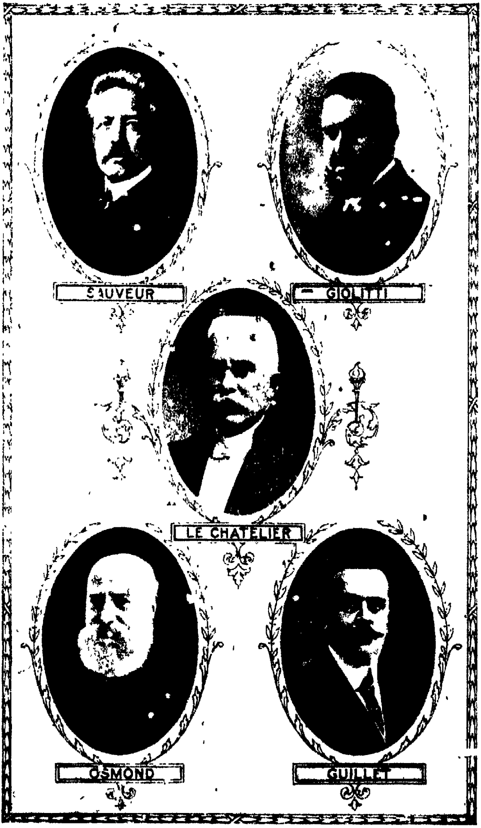

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*(see also p. xxii)* *Frontispiece*

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A CONCISE TREATISE ON THE CONSTITUTION,
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AND APPLICATIONS OF ALLOY STEELS

FOR STUDENTS, OPERATORS, AND USERS OF
SPECIAL STEELS

CHIEFLY FOUNDED ON THE RESEARCHES
REGARDING ALLOY STEELS
OF

SIR ROBERT HADFIELD, BT.
D.SC., D.MET., F.R.S., F.I.C., F.C.S., M.INST C.E., M.I.M.E., M.I.S.I., ETC.
AND WITH A FOREWORD BY HIM

BY

THOS. H. BURNHAM
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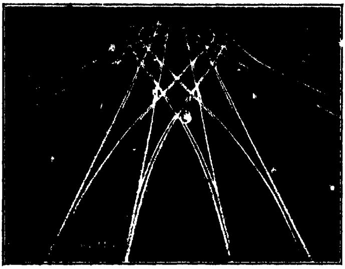

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# FOREWORD

### BY SIR ROBERT A. HADFIELD, BT., F.R.S., ETC.

THE study of iron and its alloys is, for many reasons, of very great interest and importance, one of them being on the score of economy. It may seem strange that an alloy steel, although dearer in first cost, is generally cheaper in the end than ordinary steel. Moreover, quite recently one of our well-known geologists, Professor J. W. Gregory, F.R.S., stated that if the total yearly consumption of iron and steel went on increasing in the same ratio as was the case up to the time of the outbreak of war, then the world's supply of iron ores would probably be exhausted in the comparatively short period of about 130 to 150 years. It is true that this does not immediately concern the present generation, but if the statement is correct—and the subject has been carefully considered—the time within which iron ores will become exhausted is much too near to be regarded as pleasant. Besides, too, we of to-day are to some extent stewards for the future.

The urgency of economy in the case of iron, for example, by studying methods to avoid loss by corrosion or rusting is illustrated by the accompanying diagram (Fig. A), which I have had prepared showing the world's annual production of pig iron from 1800 to 1922, together with the yearly wastage of iron and steel due to corrosion. It will be seen that the amount of iron and steel going out of use in 1921 was almost as great as the quantity of pig iron estimated to have been made in that year. Whilst much of this is recoverable as scrap, the various forms of oxidation involve a very large complete loss each year.

In this connection, special steels are of particular importance, because by their aid the consumption

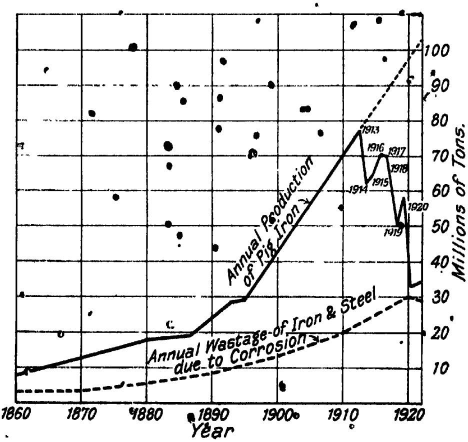

FIG. A.—DIAGRAM SHOWING THE WORLD'S PRODUCTION OF PIG IRON FROM 1860 TO 1922, AND THE ANNUAL WASTAGE OF IRON AND STEEL RENDERED UNSERVICEABLE BY THE EFFECTS OF CORROSION.

of the metal iron is reduced in quantity. For example, one ton of my manganese steel will do the work of about ten tons of ordinary iron or steel, owing to its increased durability and other qualities. In the same way, as regards my invention of low hysteresis steel, a ton of this steel is worth many times the weight of steel formerly used for similar electrical purposes. In fact, but for this important improvement, it would to-day be impossible to construct transformers, dynamos, and other electrical machinery and apparatus of the present efficient types. Moreover, many of the new special steels have resulted largely from the facts obtained by my discovery and invention of manganese steel in 1882. This led to human activities at once being turned towards and focused upon this fascinating field of research.

As quite recently stated by one of America's well-known metallurgists, Mr. H. D. Hibbard: "The discovery, as the result of systematic research, of a metal having such unique properties as the Hadfield manganese steel, started other steel-makers to see whether additional useful alloys could not be found. As a result of these activities, which eventually extended throughout the civilized world, many alloy steels have been developed of the highest importance, thus advancing materially the useful arts, and particularly the conquest of distance on land, in the air, and under the sea."

In 1888, the late Professor Floris Osmond, the well-known French metallurgist, expressed a still stronger opinion when he stated: "The Hadfield discovery and invention of manganese steel was not only the discovery of a new alloy, curious, of great scientific value, and yet useful, but in the history of the metallurgy of iron it ranked as a discovery equal in importance to that of the effect of quenching carbon steel, and was the only one of the same order which it had been reserved for our age to make." Dr. J. E. Stead, F.R.S., also said: "Hadfield had surprised the whole metallurgical world with the results obtained. The material produced was one of the most marvellous ever brought before the public."

The results of my early researches necessitated and led to the development of important new laboratory methods and practice, increased interest in metallography, accurate determination of high temperatures by pyrometers, better means of mechanical testing, and other advances.

I have given the writer of this primer permission to draw freely upon the facts set forth in the many papers, addresses, and other contributions I have written in connection with alloy steels and kindred subjects. A table of them is shown in Appendix II, and includes very complete correlated studies upon alloys of iron with manganese, silicon, aluminium, chromium, nickel, tungsten, cobalt, molybdenum, copper, titanium, and other elements.

The most important of all elements in its effect upon iron is carbon, whether in a simple carbon steel or in alloy steels; in fact, I consider that carbon steel, although technically a compound of a metal with a non-metallic element, can also be considered an alloy —the most important iron alloy extant. All steels are really alloy steels. The addition of other elements as well as carbon, makes them of binary, ternary, quaternary, or even more complex types.

The researches and studies I have carried out can correctly be termed "correlated" ones. The importance of this method of study has been strongly emphasized by my friend, Professor J. O. Arnold, F.R.S. In practically all of my researches the examination has covered and described methods of manufacture; chemical composition and analysis; preparations of the material as cast, also as rolled, forged, hammered, or pressed; heat treatment;

mechanical qualities, including elasticity, tenacity, elongation, shock qualities; hardness tests; micro-structure; electrical and magnetic qualities, including permeability and resistance; heat conductivity; resistance to corrosion and erosion; also other qualities. To understand a new steel alloy thoroughly, it is necessary to obtain practically all this information. It will be seen, therefore, how necessary it is to call in the aid of scientists of different branches of knowledge, including those representing geology, chemistry, physics, engineering, electricity, and other branches.

The quality of literature of a branch of science indicates its importance and position.

The chief writers on metallurgy in the past, that is between 1546 and 1880, do not appear to have been more than about thirty in number, including Agricola, Pettus, Reaumur, Cronstedt, Berzelius, Faraday, Mushet, Percy, and Ledebur. It will be seen, therefore, that metallurgical literature up to as late as 1880 was meagre indeed, and beyond a few books by the authors in question is of little service; in fact, one might say almost useless in connection with the science of ferrous metallurgy of to-day.

Metallurgy since about the date mentioned, that is 1880 and onwards, has become possessed of a wide range of scientific literature; scores of books deal with ferrous and non-ferrous branches respectively, all helping on our knowledge. Only quite recently this branch of science was almost regarded as an empirical one, whereas to-day metallurgy occupies an honourable position and possesses its own faculty in our universities and other educational centres.

The British Iron and Steel Institute, which was founded in 1869, has had a remarkable influence upon the progress of ferrous metallurgy. Its long list of illustrious presidents, including its founder, the late Duke of Devonshire, Bessemer, Bell, Siemens, Percy, Abel, Martin, Roberts-Austen, Carnegie, Greiner, Schneider, Stead, Lord Invernairn, and others, bears witness to this, as also does its 104 volumes and 73,000 pages, in addition to the 11 volumes, 4,500 pages, of Carnegie Scholarships Memoirs.

Its secretaries, the late Messrs. J. S. Jeans and Bennett H. Brough, and now Mr. G. C. Lloyd, have ably played their part in the development of this cosmopolitan Institute, which has a large section of foreign members, comprising leading American, French, Belgian, Italian, Swedish, Japanese, Russian and Spanish metallurgists.

At the time I invented manganese steel, in 1882, the membership of the Iron and Steel Institute, founded in 1869, was only 1,213; to-day it has nearly doubled, namely, 2,228 members. An interesting feature of the policy adopted by the Council of the Iron and Steel Institute is that it was decided, in 1916, to accept candidates for election as Associates. Persons not exceeding 24 years of age are eligible if they possess the following qualifications—Students of metallurgy taking courses at a University College or Technical School, pupils who are apprentices of metallurgists or engineers, or in metallurgical or engineering works, and persons employed in some practical or scientific capacity in metallurgical or engineering works. The subscription is exceedingly moderate—only one guinea per annum and no entrance fees—a considerably less sum than most of even the small engineering societies charge for membership. The Associateship enables individuals interested in metallurgy to obtain at once the whole benefits of the Institute with the exception of voting papers, i.e. an Associate has the right to attend all meetings and receive all notices and publications.

In addition to the Iron and Steel Institute, the Faraday Society, largely founded to help the younger men in our midst, and of which Lord Kelvin was the first President, has dealt with the more abstruse problems of metallurgy. I became President of this Society about nine months before the outbreak of war, and it was natural that, as a metallurgist, I should have turned the energies of the Society largely into the channel of scientific metallurgy. I was asked to continue in office for seven years, that is until the end of 1920, and during that term no less than seventeen symposia were held, and about two hundred papers were read, the majority of them relating to metallurgical subjects. The many students of metallurgy who will probably read this book may desire reference to these important discussions. A table showing the subjects of each symposium is therefore set out in Appendix III, including those between the years 1907 and 1914.

Many other new institutes and societies at home and abroad have been formed in this particular field of activity, such as the American Iron and Steel Institute, the British and American Institutes of Mining and Metallurgy, with probably 12,000 members, the British and American Institutes of Metals, and other Anglo-Saxon bodies dealing with metallurgy, to say nothing of scores of smaller societies here, both in London and the provinces, also in France, Belgium, Italy, Sweden, Germany, Austria, Russia, and elsewhere. There are, therefore, to-day tens of thousands of members of the profession in different parts of the world devoting constant attention to the advancement of scientific and practical metallurgy. Most of this has been accomplished in the relatively short period of fifty years.

The future march of civilization depends largely upon the scientific understanding, handling, and control of the qualities of the great and wonderful metal *Iron.* It can justly be claimed that iron is pre-eminent amongst the metals as regards its thousand and one applications. Take away iron, and it must be admitted that we should quickly go back to the dark ages, unless some great discovery of the future should render us independent of this remarkable metal.

The present primer seems to me to represent a useful attempt to bring the large subject of steel alloys into a comparatively small compass. The book is founded largely on my various research work, discoveries, and inventions, including those relating to manganese steel, low hysteresis steel, and the investigation of many other important special steels, as described fully in my papers and addresses, a full list of which to date is given in Appendix II. This will explain why my name has been somewhat frequently quoted therein.

It is hoped that the primer will be of considerable service to those who wish to make a rapid survey of this most important subject, "Special Steels," representing a branch of metallurgical science which has done so much to help on the world's progress during the last twenty-five or thirty years.

ROBERT A. HADFIELD.

# AUTHOR'S PREFACE

THE literature of special steels is rich in meritorious treatises generally dealing with some particular branch of the subject. We are indebted to Sir Robert Hadfield* for the first great development of special steels and many other contributions to metallurgy. Much information, both on the scientific and technical side of metallurgy, including special steel alloys, is also to be found in the transactions of the Iron and Steel Institute and also other societies in this country and abroad, as well as in scientific and technical journals devoted to the industry.

From neither of these sources, however, can the student, operator, or user of special steels obtain a concise technical survey of the nature and scope of this important branch of metallurgical science. The present volume is intended briefly to review current knowledge and practice in this domain, and, it is hoped, stimulate the reader to further study of this fascinating subject.

The task of planning within the confines of this small work even a synopsis of the domain of special steels was no easy one, and many interesting and important references have had to be omitted. Attention has been given, however, to steels recently developed, so that the review may be as far as practicable up to date, and it is hoped that the consideration given to working, heat treatment, and applications of special steels will be of service to users of such steels.

**THOS. H. BURNHAM.**

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* A complete list of his various Papers is given in Appendix II.

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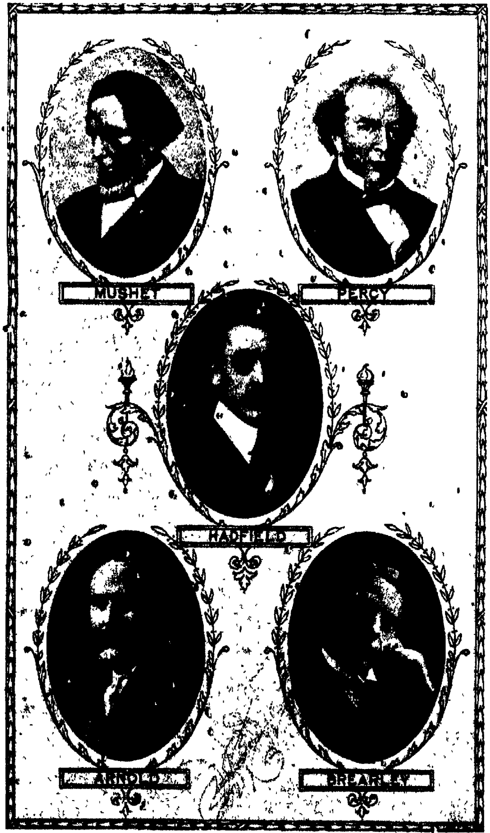

DISTINGUISHED WORKERS ON ALLOY STEELS

*(see also Frontispiece.)*

# SPECIAL STEELS

## CHAPTER I

### IMPORTANCE OF IRON AND SPECIAL STEELS

WHILST iron has been known to man from an early stage in his history it is probable that only during the last 1,500 to 2,000 years, has the human race adapted this metal to its service. Man may be designated an iron-needing creature, and it seems more than coincidence that so indispensable a metal should be so abundant in the earth. Whether iron was first hammered into spear heads by Tubal Cain or first melted on Mount Ida by a forest fire is merely imaginative speculation, but the beginnings of the metallurgy of iron and the quaint primitive processes employed are of unusual interest. It is certain that the extraction of the coveted metal was not easy whether performed in tiny charcoal-heated crucibles or in holes in the sides of hills facing the prevailing winds, with chimneys bored from the top to create a natural draught. These processes were in use before the beginning of the real iron era, which may be said to have been inaugurated in Belgium about 1340 when, by the use of coal in preference to charcoal, hitherto unheard of weights of iron were produced.

Iron and its alloys excel all other metals in the variety of their properties; their strength, their magnetic qualities, and their capacity for hardening. As an example of tenacity, this varies from about 18 tons to 150 or even 200 tons per square inch in certain cases. This immense range in properties is brought out in part by mechanical and thermal treatment, and in part by variation in the proportions of other elements which iron contains naturally or by intentional addition. Iron is never found in the pure state, and always absorbs carbon from the fuel used in extracting it from its ores. Carbon has a greater effect than any other element on iron. Iron-carbon alloys containing less than about 1·5% of carbon are known as "simple steel."

**Definition of "Special Steels."** The term "special steels" is often used broadly to designate any steels intended for purposes other than those served by the general product, but is here taken as synonymous with "alloy steels," i.e. steels which owe their properties chiefly to the presence of an alloying element other than carbon. Alloy steels may or may not contain carbon, and they vary enormously in their properties. They do not include those steels to which a small percentage of an element is added to produce a slight improvement in ordinary carbon steel as, for example, when a small amount of manganese is added to remove oxygen and neutralize the effect of sulphur, or of silicon to get rid of blowholes in steel. In the space at our disposal it is only possible to deal, in any degree of detail, with those alloy steels which have gained and maintained for themselves a place in current use.

**Modernity of Special or Alloy Steels.** In considering the development of special or alloy steels we need not go far into antiquity. Considering the important *rôle* they play in twentieth-century metallurgy, it is surprising to find that alloy steels were practically unknown about fifty years ago. As Mr. Henry D. Hibbard in the Research Narrative No. 35 (1922) of the Engineering Foundation, New York, states, Hadfield's discovery of manganese steel as a result of research practically started the study of alloy steels. Before him, the Mushets, father and son, had indeed worked out empirically a self-hardening steel for metal-cutting tools, but this application gave no such impetus to research in the field of useful ferrous metals.

It may therefore safely be said that prior to about 1865 iron metallurgy was confined practically to the combinations of iron and carbon. It should be recalled that down to the time of Huntsman's invention of crucible steel about 1740, homogeneous steel had not been fused or cast. Among the important establishments that were started in Sheffield as the result of this wonderful advance was the old works of Sanderson Brothers. It was at these works that experiments were made in 1822, at the instigation of Michael Faraday, on the effect of metallic additions to cast steel. He was desirous of obtaining better cutting tools and non-corrodible metals for reflectors. Faraday made nickel steel and found that the 3 % alloy could be worked satisfactorily. He then tried a number of rare elements including gold, silver, rhodium and, curiously enough, chromium, but we had to wait ninety years for a rustless chromium steel which would take a cutting edge. In spite of Faraday's work, alloy steel received little attention for many years, and it may be said that when Sir Robert Hadfield began his researches on the effect of other metals on the mechanical properties of iron, the metallurgy of alloy steel was practically an "unknown sea." The discovery of manganese steel by Hadfield, in 1882, demonstrated—by its remarkable and in a way subversive properties—that nothing can be taken for granted as to the properties of an alloy of iron with other elements. He quickly followed up this research by investigations of nickel steel, chromium steel, tungsten steel, silicon steel, aluminium steel and other combinations, and the many distinctions and awards Hadfield has received show that the various scientific and technical societies of the world have generally recognized the value of the discoveries emanating from this work.

It does not seem out of place here, in reference to research work on iron alloys, to quote an important statement by that well-known French scientist, the late Professor Osmond, for whom deservedly, the metallurgical world had very high respect. Referring to the Hadfield Research on "Alloys of Iron and Tungsten," Osmond remarked that "the papers formed a continuation of the series of former memoirs conceived and carried out in the same spirit. It would therefore appear reasonable to review the general results, which, directly or indirectly, were becoming more and more apparent, of these successive monographs by Hadfield.*

"In the first place, a mass of new ideas had been gained upon facts little known in the history of metallurgy, Hadfield being in a high degree imbued with respect for his predecessors, and with a sense of appreciation of their labours. The historic portion, which demanded patient and exhaustive research among the archives of the past, was not always appraised at its true value. Nevertheless, a research of this nature had, independently of its moral bearing, a practical value in sparing the investigator the trouble of recommencing work already done and from attempting what had been found useless. It also served to bring to the minds of present workers that they were the actual agents of an uninterrupted evolution, and there were few men who had exercised an influence upon the progress of this evolution comparable to that which had been brought to bear by Hadfield.

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* A full list of Sir Robert Hadfield's papers will be found in Appendix II. Although many of the papers on alloys of iron with other elements were read before 1900, the facts set forth appear to be as correct to-day as when they were first published.

"The series of his alloys had been prepared with a degree of technical skill which upset many falsely conceived ideas, resulting from imperfect preparation or from faulty manipulation. His method was a truly scientific one, by means of which all the independent variables which could be disposed of were eliminated. With the materials for investigation thus prepared, which for a long time had been unrivalled in purity, the results obtained were at once clear, coherent, and definite. Moreover, Hadfield had not used this wealth of material merely for his own personal advantage, but with never-failing generosity, of which the writer had many times availed himself, he had placed it at the disposal of those investigators who were desirous of subjecting it to their methods and of using it for their researches. Further, the useful results had rapidly gone on increasing, and from the accumulation of these the general laws had been evolved which formed the main object of all research. One fact, foreshadowed by Hadfield from the beginning, was clearly evident, namely, that all the useful foreign substances added to iron had the effect of essentially modifying the iron itself and they might be substituted for one another, in equivalent proportions, not, it is true, without modifying to some extent the secondary properties, but without altering abruptly the essential characteristics of the type ; that was to say, and this was the chief point, that there were metallurgical equivalents for substances which, though widely differing numerically from the chemical equivalents, were nevertheless qualitatively analogous.

"The three principal modifiers of iron were hardening carbon, manganese, and nickel. Their metallurgical equivalents were the respective proportions of them which would lower by the same amount the points of transformation upon the scale of temperatures. Guillet, who was at work to determine the numerical value of these equivalents with greater precision than had yet been attempted, had found that 1·65 parts of hardening carbon, or more exactly 1·65 parts of total carbon containing the maximum amount of hardening carbon was equivalent to 12 parts of manganese and to 29 of nickel. Chromium and tungsten, and probably also molybdenum and vanadium (the writer had, however, only few papers relating to the two latter) were not direct modifiers, but had as their object the maintenance of the carbon in the state of hardening carbon under the conditions of thermal treatment in which the carbon alone would separate into the state of free carbide with little activity. Their reflex action upon the carbon was itself governed by a law of equivalence.

" Now according as, with a given addition of one or several bodies, and under fixed conditions of heating and cooling, the transformations were maintained above 400° C. approximately, or were lowered so as to occur between 400° C. and the ordinary temperature, or were pushed down to a point below the ordinary temperature, there would be produced three essential types of iron, not taking account of the intermediary types which connect them. These three types would correspond respectively to the complete transformations, to the incomplete transformations, and to no transformations at all. The first type is soft iron.

"The second corresponds to hard quenched steel, and its kindred substances.

"The third corresponds to non-magnetic steels, which are subject to deformation and at the same time are very difficult to work.

"The two first had been familiar since the dawn of time, the third was due to the discoveries of Hadfield.

"Considered from this point of view the discovery of manganese steel by Hadfield no longer appeared merely as a discovery of a new alloy, curious and yet useful, but it ranked as a discovery equal in importance only to that of the effect of quenching, in the history of the metallurgy of iron, the only one of the same order which it had been reserved for our age to make."

Many other metallurgists subsequently entered this important field of investigation, and there followed wonderful advances in steel alloys which have brought about a series of revolutions in various industrial fields. Probably automobile construction has done more than anything else to increase the use of alloy steels ; its demands being so drastic that the only materials suitable are the best obtainable. The development of alloy steels was also greatly stimulated by the demands for special steels for war purposes and in connection with the aircraft industry.

**Role of Special Steels.** As Dr. Aitchison has said, almost all that the engineer builds is dependent on steel. It has been found, however, that the strengthening of ordinary or carbon steel by hardening and tempering is not sufficient for many purposes. Such carbon steels as are useful for structural or machinery purposes ordinarily do not possess sufficiently high tensile strength or reasonably high impact test or notched bar value. On the other hand, owing to the advance in knowledge of the last twenty years, these values can be greatly improved by means of heat-treatment. In addition, the effect of mass in hardening carbon steel is a drawback, the hardening not striking through the section. If, however, the steel is alloyed or fortified with other metals, a considerably greater range of mechanical properties or combination of properties is available It is due to this ability to cut down weight and retain strength, increase strength with no sacrifice in ductility, increase hardness, increase resistance to shock or fatigue, or obtain or accentuate some other property—magnetic, electrical, anti-corrosive or cutting efficiency—that there is so much special or alloy steel in use at the present time.

It has been stated that we are passing from the steel age to the alloy steel age, and it will be seen there is considerable foundation for this assertion.

Almost all known elements from aluminium to zirconium, have been introduced into steel in varying quantities and combinations, and in many cases imparting special qualities.

A few of the applications to which these special steels have been put may be mentioned briefly as an indication of the scope in which they have replaced the simpler steel—

*Nickel steel* (Chapter III) for structural and constructional purposes.

*Chromium steel* (Chapter IV) for constructional work and mining equipment, such as crusher plates and balls and stamp shoes. A recent development is the manufacture of rustless high-chromium steel, which has also excellent resistance to scaling. Rustless steels are used for piston rods in mine pumps and for bridge work.

*Silicon steel* (Chapter V) for low hysteresis sheets and springs, also for acid-resisting containers.

*Manganese steel* (Chapter VI) for points and crossings, rails, crusher and dredger parts, etc.

*Tungsten steel* (Chapter VII) for high speed tools, magnets, etc.

*Nickel chromium steel* (Chapter IX) for armour plate and projectiles, automobile parts, etc.

*Chromium vanadium steels* (Chapter X) for springs, constructional work, and tools, and for locomotive forgings, etc., where the burden has to be lightened to meet rail and bridge limitations. New heat-resisting steels are being developed for burner nozzles and automobile engine valves.

The use of special steel has proved economical in a long list of products from shovels to automobiles and parts of battleships.

The rapid growth of the industry is illustrated by the increase in the United States of alloy steel products from 181,980 tons in 1909 to 1,787,852 tons in 1918,* and although the use of special steels fell off during the recent period of depression, the consumption is again increasing as a result of the demands of the automobile and allied industries, and many new applications are being found as the result of study and research.

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* Of every 130 tons of steel made in the United States in 1909 only one ton was alloy steel, whilst in 1918 one ton in every 25 tons made was of alloy steel; the amount of alloy steel made in the electric furnace was 608 tons in 1910, compared with 290,961 tons in 1918.

As an illustration of the application of special steel to the automobile industry, reference may be made to Fig. 1, representing a view taken some time ago of a chassis assembly track at a well-known works (Harper, Son & Bean at Tipton). There are over 700 different components in the chassis of this car, including sixty made of special steels. This illustrates the wide scope of application of alloy steels, without which, the present day car, with its light weight, extreme reliability and durability, could not be produced.

The more important parts of a motor-car may be considered subjected to three main groups of stresses.

1. Alternating stresses which induce a liability to fail by fatigue.

2. Blows or shocks tending to produce sudden fracture.

3. Crushing and abrasive stresses.

The great range of mechanical properties which can be obtained with alloy steels subjected to suitable heat treatment, render these materials particularly suitable for a great variety of applications involved. The steel for each part of the car must have the necessary qualifications for its particular work. For example, hardness in gears, toughness and high elasticity in axles and crankshafts.

When considering alloy steels, however, it must be borne in mind that composition is a means and not an end. In other words, the special element is only added if the desired mechanical, magnetic or other property cannot be obtained a cheaper way.

FIG. 1.—MOTOR CAR CHASSIS ASSEMBLY TRACK.

In each chassis there are 70 components of alloy steel, in this case made by Messrs. Hadfield, of Sheffield.

In many cases also the present consumer of alloy steel has at his command more than one type of steel which is satisfactory as regards some particular property required, and he is then influenced in his choice by the relative economy of the alternative materials in the various manufacturing processes to which they are subjected.

**Achievements of British Metallurgists.** Metallurgy is a cosmopolitan science, and other nations have contributed very useful and important work to its development, but it is interesting to note that the metallurgy of iron and steel has advanced to its present position mainly from the fundamental discoveries of British metallurgists. To enumerate the names of only Dud Dudley, Huntsman, Cort, Neilson, Bessemer, Mushet, Siemens, Sorby, Snelus, Whitworth, Bell, Thomas and Gilchrist will be sufficient to indicate the truth of this statement. It is important that the student should realize this, as he is apt to be misled in reading some pre-war publications in which the claims set forth for German contributions have been greatly exaggerated.

On the other hand, the important work done by the early Scandinavian metallurgists has not been sufficiently recognized. It must not be forgotten that Swedish scientists discovered the following elements—

Barium
Cerium
Chlorine
Cobalt
Didymium
Lithium
Molybdenum
Nickel
Oxygen
Scandium
Selenium
Silicon
Tantalum
Thorium
Tungsten
Vanadium
Ytterbium
Zirconium

Attention was drawn to this subject by Sir Robert Hadfield in a recent lecture* on the work of the metallurgical chemist, which has been widely circulated and approved by the leading chemists of to-day. In a chapter dealing with this subject, it is pointed out that although the Germans have played a very useful part in the development of metallurgical chemistry, a brief review of the work done by our own chemists shows that we have nothing to fear from a comparison; in fact, it is indicated that chemical supremacy rests with the English-speaking people. In the same chapter two tables are given, recapitulating the most distinguished names in connection with chemistry both pure and applied, and, although it is not possible to indicate the relative prominence of the individuals, an examination of the lists shows the preponderance of British workers. Indeed, the science abounds with names of English rather than Teutonic investigators. It will generally be found that the Teuton was very diligent in applying the fundamental discoveries of his neighbours, and this earned for him such a reputation that it required a great war to disillusion the rest of the world.

It seems to be a national trait of ours to indulge in self-depreciation. This sometimes tends to decrease our confidence in ourselves, and leads to a belief in the superiority of German workers. Marshal Foch, when asked whether he found his academic studies to be of immediate service on the field of battle replied, "No, not altogether, but they give me confidence." It is this confidence in life which is so important and so essential—the acquired confidence, which comes from knowledge.

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* See Appendix II, Section 17, Paper No. 132. Published by Messrs. Chas. Griffin & Co.

Sir William Tilden pays tribute to the pioneer work done by Scandinavian metallurgists and in particular considers Berzelius to be one of the really great chemists of history. He points out that while it is scarcely possible to estimate the relative positions of the nations by enumeration of names, another comparison may be made by reference to the publications in each country. Perusal of the Journal of the Chemical Society shows a magnificent record of British work done, the quality of which will bear comparison with that of any recorded by Teutonic journals.

Sir Edward Thorpe thinks that justice should be done, as it always is by British writers, to the merits of Scandinavian chemists, not only in their discovery of chemical elements, but also in the service they have rendered as regards theory. One of our leading public men, Lord Riddell, has recently stated that he considers it of considerable importance to bear in mind the achievements and positions of British metallurgists and chemists, particularly considering the attacks made on our nation's standing by people who should know better.

In considering the contributions of different countries to the progress of ferrous metallurgy, that of Italy deserves mention. Professor Federico Giolitti has done excellent work with regard to alloy steels and the study of cementation ; also, concerning the heat treatment of steels for mechanical constructions and machine parts. The Iron and Steel Institute awarded him the Bessemer Gold Medal for 1919

# CHAPTER II

## CONSTITUTION AND MANUFACTURE OF SPECIAL STEELS

**Constituents of Carbon Steel.** In spite of all that has been written about iron and steel, many hazy notions regarding them still exist. A good deal of help, however, towards the understanding of alloy steels is afforded by constitutional diagrams which illustrate the effect of the alloying elements. The parent of these diagrams is the iron-carbon diagram, shown in Fig. 2. The constituents are as stated briefly below. It may be added that the theory formerly held by some metallurgists of the existence of a hard or beta form of iron has now been abandoned, newer facts which have come to light having proved that it is not tenable.

*Ferrite* (Fig. 3*), is pure iron, soft, ductile and relatively weak, having practically no hardening power, and crystallizing, if growth were free, in the cubic system.

*Austenite* (Figs. 4 and 8), named after Sir William Roberts-Austen, F.R.S., is the solid solution of carbon in $\gamma$-iron, formed at high temperatures, i.e. above the critical range of steel, which may sometimes be obtained by quenching rapidly from such temperatures. This constituent is not of constant composition, the carbon varying from a trace up to 2%. The retention of austenite is assisted by the presence of some alloying elements such as manganese, nickel, etc.

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* Figs. 3–8 are line drawings prepared from microphotographs to illustrate the characteristic structures of the constituents.

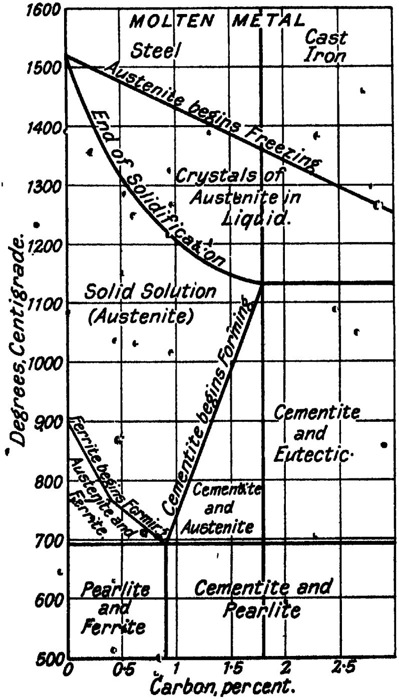

FIG. 2.—CONSTITUTIONAL DIAGRAM OF CARBON STEELS.

*Martensite* (Fig. 5), named after the German metallurgist, A. Martens, is the first stage in the transformation of austenite in cooling through the critical range, and differs from austenite only in structural aspect. Probably the solute particles are

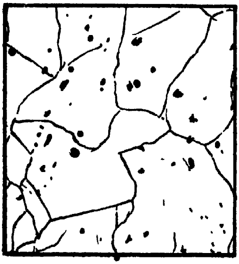

FIG. 3.—FERRITE.
Magnification 100 diameters.

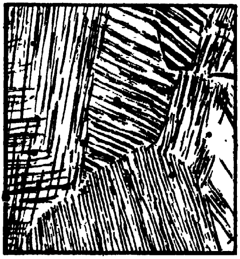

FIG. 4.—AUSTENITE.
Manganese steel, water-toughened
Magnification 600 diameters.

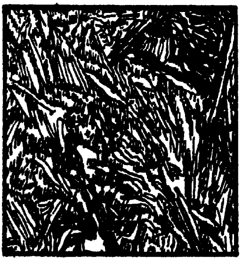

FIG. 5.—MARTENSITE.
Eutectoid steel quenched.
Magnification 400 diameters.

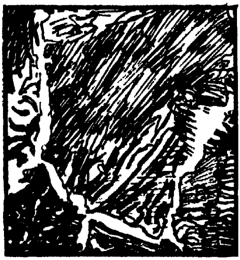

FIG. 6.—PEARLITE AND CEMENTITE (WHITE).
1·3 carbon steel.
Magnification 500 diameters.

in critical dispersion which may account for its extreme hardness. It is formed by rapid quenching, which is, however, not sufficiently drastic to preserve austenite. It is usually acicular in structure.

*Cementite* (Figs. 6 and 8) is the carbide of iron corresponding to the formula $Fe_3C$ and consists of 6·6% of carbon and 93·4% of iron. It is very hard and brittle, and has little strength. It may occur admixed with carbides of alloying elements such as $Mn_3C$.

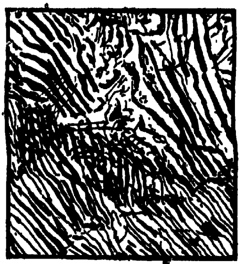

FIG. 7.—PEARLITE.
Eutectoid steel. Magnification 750 diameters.

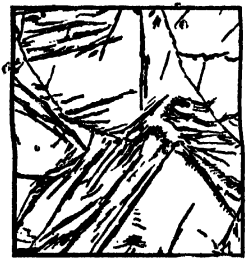

FIG. 8.—CEMENTITE (BLACK) AND AUSTENITE (WHITE).
Manganese steel as cast. Magnification 600 diameters.

*Pearlite* (Fig. 7), so called from its characteristic appearance under the microscope, is a mechanical mixture of cementite with a definite amount of ferrite, the resultant containing about 0·9% of carbon. A steel consisting entirely of this constituent is known as eutectoid steel. It has a maximum strength and low ductility. It usually occurs in lamellar formation, i.e. consisting of stratified layers of cementite and ferrite.

*Troostite* is the first breakdown product of martensite during the resolution on heating of solid solution (austenite) into pearlite. It is also formed when quenching is not sufficiently rapid to preserve martensite, but too drastic for the formation of pearlite. It is almost structureless.

*Sorbite*, named after Dr. Sorby, of Sheffield, represents another and later phase of the translation of the quenched solid solution into lamellar pearlite. It may be considered to be imperfectly developed pearlite, the cooling having been sufficiently rapid to prevent the formation of distinct lamellae.

The hardness of the micro constituents of steel as determined by Mr. T. G. Elliot, F.I.C., of the Hadfield Research Laboratory, are as given in Table I.

TABLE I

HARDNESS NUMBERS OF MICRO CONSTITUENTS OF STEEL

| Constituent. | Brinell Hardness. | Scleroscope Hardness. |
|---|---|---|
| Ferrite . . . . | 82 | 10 |
| Austenite . . . | 204 | 28 |
| Martensite* . . | 578 | 76 |
| Troostite* . . . | 444 | 60 |
| Sorbite* . . . | 332 | 49 |
| Pearlite* . . . | 196 | 30 |

* The hardness of these constituents is higher in steels containing chromium, chromium-nickel, etc.

**Constituents of Alloy Steels.** In alloy steels there are no more and no fewer constituents than in carbon steels, but the addition of the special elements increases the ease with which given constituents may be produced. Special steels are usually spoken of in terms of composition and heat treatment, but attention should always be paid to the constituents as they are equally or more important. Special elements may act in the following ways—

(1) Tend to keep the carbon in solution.

(2) Tend to aid in throwing it out of solution as a simple or compound carbide.

(3) Tend to keep the carbon in solution within certain limits and to throw it out beyond these limits.

The alloying elements may, in fact, be considered as catalysts which accelerate or retard the rate of solution and precipitation of carbide. In addition, they influence the rate of collection of small particles into large ones. Chromium and tungsten associate principally with the carbide and, on heating an annealed steel, go into solution at higher temperatures. Nickel and manganese are more inclined to be with the iron and go into solution at a lower temperature. Alloy steels with one special element are called *ternary steels*, the three constituents being iron, carbon and the special element. Steels containing two special elements are called *quaternary steels.*

The able French metallurgist, Guillet, conceived a theory of ternary steels which forms a valuable guide to their constitution and properties. Upon the introduction of a third element into carbon steel, the steel remains pearlitic at first, but as the amount of the special element is increased, the carbon remaining constant, the steel becomes martensitic, then austenitic, or sometimes cementitic, depending on the chemical action or alloying powers of the special element. By keeping constant the percentage of the special element, a similar transformation from pearlitic to martensitic and then austenitic conditions may be effected by raising the carbon content. The greater the amount of carbon, the smaller the proportion of the special element needed to cause a structural transformation. The greater the amount of special element the smaller is the proportion of carbon needed to cause a structural change. It should, of course, be noted that there are no sharp lines of demarcation between the different types of structure mentioned.

It will be seen that constituents may be formed during the slow cooling of many special steels which can only be produced in carbon steels by very rapid cooling through the critical range. The production of martensitic and austenitic structures on slow cooling is generally thought to be due to the action of the special element in depressing the position of the critical point to a low temperature so as either to permit of only a partial transformation or suppress the transformation altogether. It appears that if the critical point remains above 300° C. the steel becomes pearlitic on slow cooling. If the critical point is below this temperature the steel becomes martensitic or, if the critical point be at or below atmospheric temperature, the structure is austenitic. By cooling austenitic nickel-steels to the temperature of liquid air, a partial transformation takes place, and they become martensitic and magnetic again. The above suggestion as to the production of constituents is very useful but, in the light of recent research, may need modification or amplification. At least in the case of austenitic manganese-steels it is not the only possible explanation.

**Influence of Special Elements.** The influence of special elements on the critical points varies greatly; some elements do not yield austenitic or even martensitic steels, and a few raise the location of the critical points.

**Pearlitic Special Steels** may be divided into those not very sensitive to annealing such as nickel and silicon steels, and those which are sensitive, viz., manganese, chromium, vanadium, tungsten and molybdenum steels. The structure is similar to, but often finer than, that of the corresponding ordinary carbon steels. These steels are generally superior to ordinary carbon steels as regards elastic limit and ductility, and show a better resistance to shock. Practically all structural steels belong to this type.

**Martensitic Special Steels** are hard, brittle and unforgeable in the cold. Their uses are limited, but they possess a fairly high degree of stability, being little affected by tempering at 300° C. or even higher temperatures, and they are therefore used for cutting tools (*see* p. 104).

**Austenitic Special Steels** are not so hard as martensitic steels, but are moderately strong and ductile. They have a low elastic limit but high shock values, and are resistant to wear and tear. They should be free from separated carbides ; if present, these may be re-absorbed by heating to a high temperature (1,000° C. or above) and quenching in water (*water toughening*) or in oil. These steels can only be used where a low elastic limit is not dangerous to the safety of the article or structure, and price is not serious.

**Cementitic Special Steels** contain double carbides of iron and the special element. These are dissolved in a martensitic structure by cooling from a high temperature. The steels retain their hardness up to a visible red heat.

**Classification of Iron Alloys and Prediction of Properties.** Attempts have been made to classify the alloys of iron with various elements, so as to predict the properties that might be expected if other elements were used.

Osmond arranged the elements in the order of their atomic volumes (*see* Table II), and considered that those with atomic volumes less than that of iron lowered the change points, while elements with

TABLE II

PHYSICAL CONSTANTS OF ELEMENTS USED IN THE MANUFACTURE OF ALLOY STEEL

| Element. | Symbol. | Atomic Weight. | Specific Gravity. | Atomic Volume. | Melting Point °C. |
|---|---|---|---|---|---|
| Carbon . . . | C | 12·0 | 2·2 | 5.5 | 3450* |
| Nickel . . . | Ni | 58·6 | 8·75 | 6·7 | 1452 |
| Cobalt . . . | Co | 58·9 | 8·72 | 6·75 | 1490 |
| **Iron . . . .** | **Fe** | **55·8** | **7·86** | **7·1** | **1530** |
| Copper . . . | Cu | 63·5 | 8·93 | 7·12 | 1083 |
| Manganese . . | Mn | 54·9 | 7·42 | 7·4 | 1230 |
| Chromium . . | Cr | 52·0 | 6·92 | 7·5 | 1510 |
| Titanium . . | Ti | 48·0 | 5·28 | 9·1 | 1850 |
| Vanadium . . | V | 51·2 | 5·50 | 9·3 | 1720 |
| Tungsten . . | W | 184 | 19·10 | 9·6 | 3000* |
| Aluminium . | Al | 27·1 | 2·56 | 10·6 | 659 |
| Silicon . . . | Si | 28·2 | 2·50 | 11·2 | 1420 |
| Molybdenum . | Mo | 96·0 | 8·5 | 11·3 | 2500* |
| Uranium . . . | U | 238 | 18·68 | 12·7 | 2400* |
| Zirconium . . | Zr | 90·6 | 4·15 | 21·8 | 1700 |

* The values given for temperatures higher than 1,500°–2,000° C. are necessarily somewhat approximate.

higher atomic volumes raised the temperature of transformation. Subsequent work has indicated, however, that this conception is scarcely adequate.

Other investigators have attempted to show a relation between the position of the elements in the periodic table and their effect on the properties of iron and steel. In Group IV, for example, silicon, titanium and zirconium have to a certain extent similar deoxidizing effects, and the effect of uranium on steel was to some extent predicted from those of chromium, molybdenum and tungsten (all in Group VI).

It seems probable that the action of the various elements on iron and steel is governed in some way by their atomic and molecular structure, but a good deal of work remains to be accomplished before such a relation can be derived. Help may be given by the new method of X-ray analysis,* recent work in this field by Hall, Westgren and others having determined the lattice structure or arrangement of the atoms in iron crystals and the effect on this structure of the introduction of atoms of alloying elements. During Sir Robert Hadfield's term of office as President, from 1914 to 1920, an important symposium, originated by him, was held by the Faraday Society on this subject (in 1919), when fifteen papers were read, comprising 150 pages ; *see* Appendix III.

**Manufacture of Alloy Steels.** The manufacture of alloy steels presents greater difficulties than that of plain carbon steels, and the former are more liable to surface defects and tiny cracks due to the inability of the metal to distort. Alloy steel should be sound and the surface smooth and free from folds and kinks.

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* See also *Industrial Applications of X-Rays*, by P. H. S. Kempton, uniform with this volume (Pitman, 2s. 6d. net).

Defective skin can however, be removed by rough turning. The best melted steel should pipe, this being taken care of by properly feeding the ingot. It should be remembered that steel-making ability is often as important as the chemical composition of the steel. There are characteristics not shown in the analysis which distinguish between good and bad quality. Steels of identical analysis may therefore differ considerably. It has frequently been assumed that if a certain amount of an alloy is useful, further additions are better, but this is by no means the case with ferrous alloys. The study of such alloys should always be a correlative one, otherwise wrong conclusions may be reached; the various chemical, mechanical, and physical properties should be studied in correlation with each other.

The manufacture of high quality steel depends on the human element engaged and on never ceasing care in the operations. Poor melting and pouring practice give rise to faulty structure such as "snow flakes," which are also frequently associated with dirty steel. In most cases, except for free-cutting properties, sulphur and phosphorus should be kept as low as possible. There are other inclusions, non-metallic and non-ferrous which are present in most steel in greater or smaller amounts. Analysis does not show them, and they frequently escape attention.

A prerequisite of faultless finished steel is perfect ingots made of homogeneous material. The effect of unduly large crystals is to make the ingots tear in working, which deforms and thus refines the crystals. The size and shape of crystals are controlled by a number of factors.

Alloy steels are chiefly made by the *crucible*, *electric furnace*, and *open hearth* processes. The Bessemer process has in some cases, when properly handled, given excellent results, but ordinarily is not so uniform in quality. Steel is made in the crucible and the electric furnace in relatively small quantities, but of the highest quality. In the open hearth furnace steel is made in large quantities, but generally does not attain the highest quality.

*Open Hearth Process.* The open hearth process (Fig. 9) is used for a large variety of products, and has a high output. The composition and temperature of the bath are under good control, and the temperature is independent of the means used to purify the metal. The lining of the furnace may be of acid or basic material. Only in the latter case does purification of the steel take place, most of the phosphorus and some of the sulphur being removed. Acid open-hearth steel is generally considered superior to that made on a basic hearth, but this is probably due to greater difficulty of control in the latter case.

The method of operation in making alloy steel is much the same as for making carbon steel, the differences occurring in the process of finishing, i.e. in making additions required for the kind of steel desired. These additions are generally made just before or after tapping, but the methods differ somewhat. Ferromanganese and spiegel are usually added molten in the ladle. In the case of nickel, either nickel-steel scrap or pig nickel may be charged half an hour or more before tapping the charge. Chromium is added in the form of ferro-chrome, just long enough before casting for the alloy to become thoroughly mixed through the charge, but unless care is taken a certain proportion is lost through oxidation. Ferro-silicon is added in the ladle, and vanadium in the form of ferro-vanadium is sometimes added

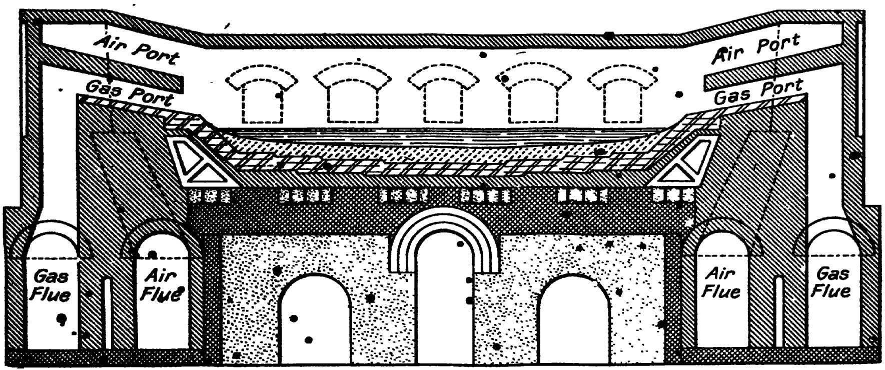

FIG. 9.—OPEN HEARTH FURNACE (SECTION).

to the stream of metal flowing into the ladle. Copper is added solid to the bath about twenty minutes or so before tapping. There is usually a loss of the element added which varies for each element and according to the working conditions. There are

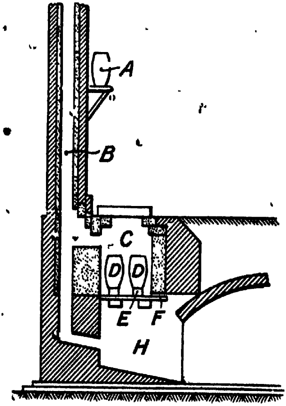

FIG. 10.—CRUCIBLE FURNACE, COKE FIRED (SECTION).

*A* = Crucible being dried.
*B* = Chimney.
*C* = Furnace.
*D* = Crucibles containing charge.
*E* = Stand for crucible.
*F* = Firebar.
*H* = Ash-pit.

also other methods of adding the alloys to suit the conditions prevailing in different plants.

*Crucible and Electric Furnace Processes.* For many years high grade steels were made by the crucible process (Fig. 10), but of recent years there has been a rapid adaptation of the electric furnace* for refining steel. At the present time complex alloy steels are made with precision in the electric furnace (Fig. 11), almost equal in grade to the best quality crucible steel.

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* See also *The Electric Furnace*, by F. J. Moffett, uniform with this volume (Pitman, 2s. 6d. net).

Fig. 12 shows the tapping of a 6-ton Héroult electric furnace with an observer taking the temperature of the molten stream of steel flowing into the ladle by means of an optical pyrometer.

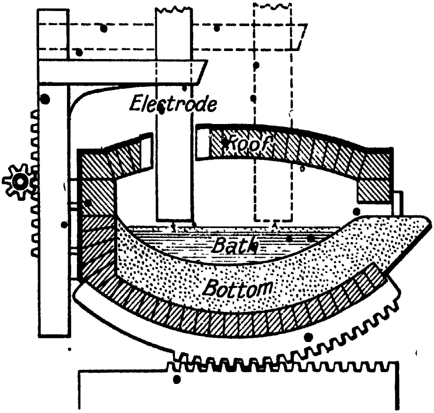

FIG. 11.—ELECTRIC FURNACE (SECTION).

The following are the characteristics of electric melting, to which the high quality of the products is due. A high temperature is obtainable, and can easily be maintained; the heating agent is clean; there is no evolution of harmful gases; and an oxidizing, reducing or neutral atmosphere can be maintained as desired. The whole operation of

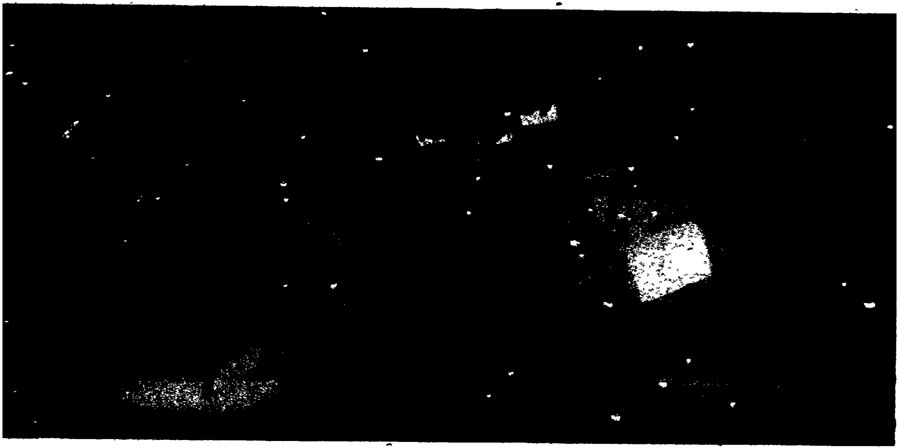

Fig. 12.—Tapping a 6-ton Héroult Electric Furnace at the Hecla Works, Sheffield.

During the war Messrs. Hadfields had twelve electric furnaces at work and melted about 120,000 tons, the greater part from turnings and other forms of scrap which would otherwise have been of little service.

refining the steel is under almost complete control. In the oxidizing period all the oxygen is introduced into the furnace in the solid form. In the reducing period the bath is deoxidized by carbon. During the finishing period the conditions are either reducing or neutral. The loss of the alloying elements is reduced to a minimum, and finishing the steel in the furnace leads to greater uniformity. The alloys required may be added as soon as the slag conditions permit; ferro-silicon is added about 10 to 15 minutes before tapping. The electric furnace process is the only one in which impurities are not added to the steel by the operation. In the open hearth, the metal is subjected to the action of the air and gas, while in the crucible process the steel may take up carbon and silicon from the crucible.

The electric furnace is sometimes used to refine molten open-hearth steel, and is valuable for remelting alloy steel scrap without loss and making a high grade product therefrom. The raw materials used in the electric furnace are cheaper than those for the crucible, large castings can be made from one heat, and the steel is free from impurities to a high degree.

Of the many electric furnaces in use no one can be said to possess any great advantage over the others, though the Héroult type has been the one most generally adopted. From the economical point of view the electric furnace seems destined to progress conjoined as a duplex operation with the open hearth.

It is not easy to compare crucible and electric furnace steel, as each possesses its own distinctive field of use. The crucible process is not suitable for manufacturing large quantities of low-carbon alloy steel, but the electric furnace is ideal for this. The crucible process yields the highest quality tool steel. Some comparative tests which have been made showed that square rods of a 1·1% carbon crucible steel gave greater bending angles and greater scleroscope and ball hardness in the hardened state than did a similar electric furnace steel. The practically sealed crucible gives a near approach to ideal conditions, i.e. melting in the absence of oxidizing conditions and out of contact with the products of combustion, and in small units. It is probable that the silicon is in the nascent condition in the crucible, and helps to remove the harmful effect of the gases. Crucible steel is also free from flakes. The electric furnace yields larger heats and therefore larger ingots. The ingot troubles are found to be roughly proportional to the square of the diameter. Pipes, seams, segregations and surface imperfections are also apt to increase with the size of the ingot. Metals which oxidize easily, e.g. vanadium, chromium and manganese, are readily handled in the electric furnace, and there is better solution, diffusion and homogeneity. If it is a question of obtaining steel with the lowest possible sulphur and phosphorus content, and generally for most applications the electric furnace process is to be preferred.

Whilst the electric process has made great strides, crucible steel of the highest quality still continues to be made in large quantities, chiefly in Sheffield.

**Mechanical Treatment.** In order to develop the mechanical properties of steel to the highest degree, it is subjected to mechanical work, either by hammering, pressing, or rolling. A 3-ton steam hammer capable of forging ingots up to 14 in. diameter into billet form is shown in Fig. 13. Forging presses may be arranged to act vertically or horizontally, and large

FIG. 13.—A 3-TON STEAM HAMMER CAPABLE OF FORGING DOWN 14-IN. INGOTS INTO BILLET FORM.

presses of both types are illustrated in Figs. 14 and 15. Fig. 14 shows a 1,500-ton vertical press, which can deal with forgings up to 15 tons in weight and 22 in. diameter. A number of marine forgings produced in this press are shown in the front of the photograph. Fig. 15 shows a giant horizontal press which is used for piercing or extruding gun tubes, projectiles, and similar large size work. Messrs. Hadfields, of Sheffield, had three of these at work day and night during the Great War.

The benefits derived from mechanical treatment consist in forcing the particles into intimate contact, closing up cavities, and refining the crystalline structure. Working not only improves the mechanical strength, but influences the hardness and ductility, the amount of the change depending on the work done and the temperature at which it is carried out. The ultimate aim of working the steel is to secure a fine uniform grain, and this is obtained by thoroughly forging or rolling the metal at a temperature somewhat above its critical point. A sharp change in structure due to working takes place as the $Ar_1$ critical point of the steel is passed. Above this point the carbon is dissolved to form a homogeneous mixture and, owing to the plasticity of the metal, distortion due to working does not produce a permanent strain, and the grains are broken up into smaller ones. Below the critical temperature the aggregate of metal and carbide is permanently distorted or strained. Steel can be worked " cold " to a certain extent, but it must be annealed in order to remove internal strains. The higher the temperature, the more easily the steel is deformed, but it is essential to keep the working temperatures within certain well-defined limits. Steel must not be heated to a temperature at which

Fig. 14.—A 1,500-ton Vertical Forging Press at the East Hecla Works, Sheffield.

it assumes a semi-fluid state or it will be "burned." The temperature of forging high carbon steels should not ordinarily exceed about 1050°C. Nickel steel is heated to about 1090° C., chromium-vanadium steel to even higher temperatures, and copper steels to about the same temperature as the corresponding carbon steel. Owing to the poor conductivity of most alloy steels, the ingots must be carefully warmed and preheated before being raised to a forging temperature, as they will not absorb heat suddenly without cracking. Owing to the greater strength and less plasticity of alloy steels at high temperatures, more energy is generally required to work them than carbon steel, e.g. high speed steel is difficult to forge hot. Manganese, however, improves the rolling or forging qualities.

As regards the efficacy of the three methods of working—hammering, pressing, and rolling—each has a field of its own. For example, some intricate shapes cannot be rolled. A high degree of refinement results from hammering, provided the amount of reduction is large. Much depends on the use of a hammer of the right size; in other words the hammer should be heavy enough for the work.* Under the impact of the hammer scale is removed. The contour of the dies used in forging must be such that the metal flows evenly and gradually to the finished shape, and is not violently displaced.† In working under a press the kneading of the material penetrates deeply. Extraordinary care and attention

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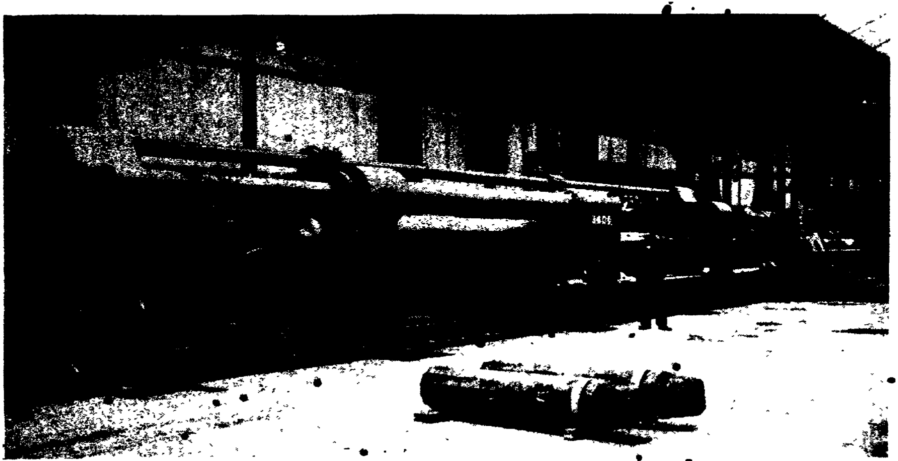
* An approximate rule for finding the suitable capacity of a steam hammer is to multiply the largest cross section (in sq. in.) to be worked by 80. The product will be the rating of the hammer in lb.

† See also *Drop Forging*; by H. Hayes, uniform with this volume (Pitman, 2s. 6d. net).



*Hadfields, Ltd., Sheffield.*

Fig. 15.—A 2,000-ton Horizontal Forging and Piercing Press.

are given to every detail of forging. Rolling, although perhaps not producing the best quality bars, has come to be used most widely, and is very valuable for its large output. Hammer and press work is slower and more expensive to operate. The temperature is likely to be higher in rolling than forging.

In forging tool steel it is particularly necessary to ensure uniform heating, and the correct range of temperature from beginning to end of the operation. At about 400° C., tool steel is subject to blue brittleness or sensitiveness to shock, especially in very hard steel containing free cementite. It is advisable closely to follow the makers' instructions to obtain satisfactory results.

**Rolling Special Steels.** Fig. 16 shows the 11-in. and 14-in. rolling mills at Messrs. Hadfields' East Hecla Works, Sheffield, for rolling billets of various commercial sizes into round and square bars. These mills are used for the production of high tensile steel for motor-cars and commercial vehicles, spring steel and other special steels ; they are of an exceptionally robust character to withstand the abnormal stresses arising from the rolling of special steels of this description.

Both mills are of the continuous-running bar type, each driven direct by an electric motor having a flywheel and flexible coupling interposed between the motor and the mill. The mills are complete with the usual reeling machines, shears and hot saws, etc., all driven by individual electric motors, each machine being situated in the best position for handling the material in the progressive stages after leaving the rolls. A roll-turning department is provided in which are situated electrically driven roll-turning lathes and the full equipment for turning

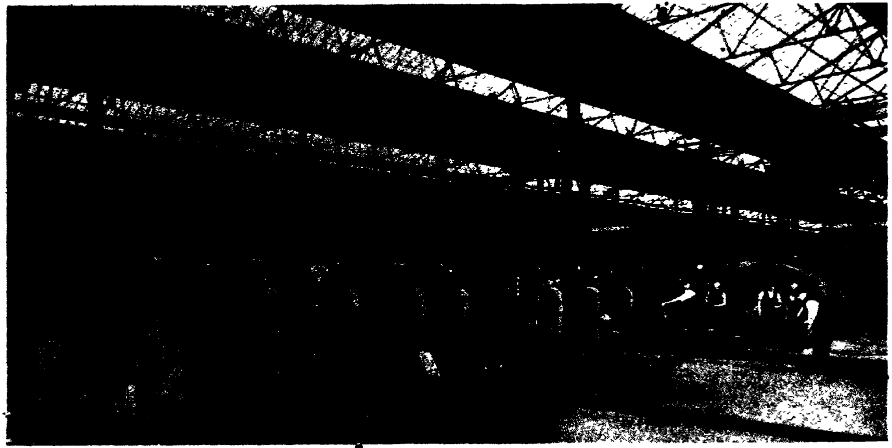


FIG. 16.—ELECTRICALLY-DRIVEN 11-IN. AND 14-IN. MILLS AT THE EAST HECLA WORKS, SHEFFIELD, FOR ROLLING ALLOY STEELS OF HIGH TENACITY.

rolls. Furnaces of the semi-gas recuperative type are used to heat the billets before they enter the rolls; the billets are thus heated in the shortest possible time with a minimum of fuel consumption.

The control of temperature is of extreme importance in the manufacture of special steels, and in rolling these materials it is essential, not only to start the operation with the ingots well soaked at the correct temperature, but also to roll at such a rate as to finish at the correct temperature.

The whole equipment is laid out on the most modern lines, and is arranged for obtaining maximum production with minimum labour. Overhead electric travelling cranes handle the raw and finished materials also changing rolls, etc., and the lofty, well lighted and well ventilated building provides an abundance of floor space which is so essential to the successful operation of rolling mills.

Fig. 17 shows a reversing 28-in. blooming and finishing mill of the latest type, recently laid down by Messrs. Hadfields at the same works, which is believed to be the first having for one of its main objects the production of manganese steel rails. This mill is capable of rolling down 15-in. square steel ingots 5 ft. long, weighing 25 cwt., and reducing them at one heat to 2½-in. square billets. The normal output is approximately 1,500 tons per week, or say 15 tons per hour, with a maximum output of 20 tons per hour for occasional short periods. The mill will also roll Hadfield "Era" manganese steel ingots into rails up to the heaviest section in demand having a maximum length of 55 ft. rolled, say, 45 ft. finished.

As shown by Fig. 17, the mill comprises one cogging and one finishing stand. The cogging rolls are

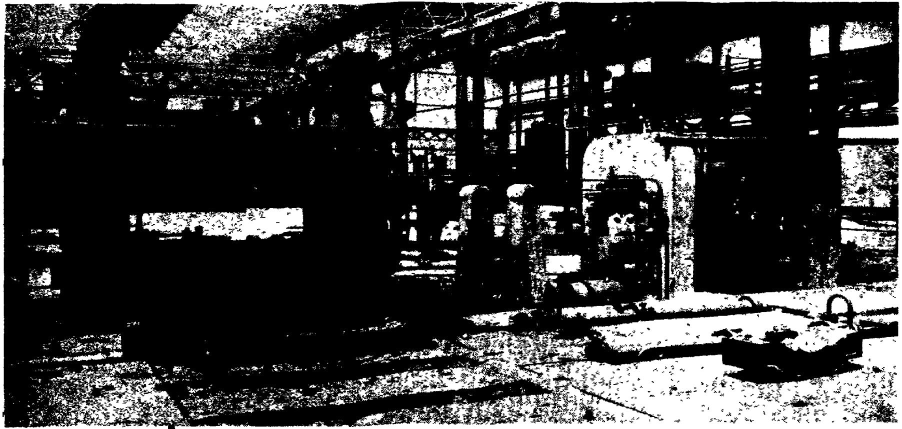


FIG. 17.—ELECTRICALLY DRIVEN 28-IN. MILL CONSTRUCTED IN 1922 AT THE EAST HECLA WORKS, SHEFFIELD.

This photograph shows roughing and finishing stands for rolling special steels including manganese steel rails.

28 in. diameter and 7 ft. long, and the finishing rolls 28 in. diameter and 6 ft. 6 in. long. The total weight of the mill is about 1,600 tons, including the electrical equipment which weighs approximately 400 tons. The main rolls were manufactured throughout by Hadfields, and are of their special quality carbon forged steel with machined fluted wobbler ends. The hydraulic shears are of the up-cutting type complete with hydraulic intensifier arranged for a maximum power of 1,000 tons and capable of shearing "Era" manganese steel blooms when hot up to 10 in. square. The hot saw is of the horizontal sliding type, fitted with a blade 60 in. diameter and driven by a 75 h.p. motor.

The mill motor is rated at 3,200 h.p., with a maximum output of 11,600 h.p. for short periods. It is capable of exerting a constant torque of 125 ton-ft. from standstill to 60 r.p.m. in either direction, and gives a constant horse-power of 3,200 h.p. between the speeds of 60 and 120 r.p.m. The overload capacity corresponds to a torque of 453 ton-ft. between standstill and 60 r.p.m.; and 11,600 h.p. between the speeds of 60 and 120 r.p.m.

The cast steel flywheel is of the built-up type, 11 ft. 6 in. diameter and weighing 30 tons. The flywheel set, which consists of an 1,800 h.p., three-phase motor on the same shaft as two dynamos of 6,000 h.p. and a 30-ton flywheel, is interposed between the power lines of the Sheffield Corporation and the main mill motor in order to provide for the control of the latter and equalize the load on the supply mains. The main mill motor is capable of being reversed from full speed in one direction to full speed in the other direction in three or four seconds.

The appliances for carrying out the requisite treatment of the manganese steel rails are arranged at the side of the ingoing run-out by which the rolled material is conveyed to the saw. A noteworthy feature is an electrical-telegraph system established between the control platform and the electrical equipment house for the transmission of orders between the mill driver on the platform and the attendant in the electrical equipment house.

The hydraulic water service to the mill is arranged for a working pressure of 2 tons per sq. in. and is supplied by a set of three throw pumps driven by a 175 h.p. motor. The floor surrounding the mill is finished off neatly, the live roller gear being below the floor, and the latter representing an even plated surface all over with the exception of the live rollers which necessarily project slightly above the floor level. Provision is made for turning the main rolls in one bay of the mill where there is ample space for the storage of the rolls.

**Heat Treatment.** Until about 1890 the subject of heat treatment of steel had attracted little scientific attention. Subsequent inventions, however, which required the lightest possible steel parts with the highest possible strength and other specific properties, necessitated the use of alloy steels and made it essential that these steels should receive the proper heat treatment to develop their properties to the highest degree. Developments in the manufacture and heat treatment of alloy steels have occurred concurrently, heat treatment being of the highest importance in contributing to the superior qualities of the product; in fact in special steels it is always essential that the heat treatment given be careful and precise—not that special difficulties are involved but that the benefits accruing from the use of alloy steels may not be commensurate with the increased cost unless the potential physical properties of these steels be fully developed.

The object of heat treatment is to secure perfect diffusion of the carbon present and a fine grained structure free from brittleness. In order to fix the best treatment it is necessary to know the temperatures of the critical changes, the critical speed of cooling, and the rate of tempering. Since the special elements influence the position of the critical points, these should be determined in each case. When all the constituents of the steel have passed into a state of solid solution, the greatest refinement of grain is obtained, but owing to hysteresis it is necessary, in practice, to heat steels a little above their critical ranges.

The great work of Professor Henri Le Chatelier, of the Sorbonne, in the introduction of thermo-electric pyrometers and his contributions to the development of the whole subject of pyrometry, have been of the highest importance. In this connection it may be mentioned that in the Address delivered on the occasion of his Cinquantenaire Scientifique at Paris, on 22nd January, 1922, Professor Le Chatelier stated that it was due to the inspiration of Sir Robert Hadfield that he took up research work in connection with optical pyrometry. It was on this occasion that Le Chatelier was presented with a gold commemoration medal and a subscription with which he decided to found the Henri Le Chatelier Biennial Prize for Industrial Research.

As an example of the broadmindedness of this great Frenchman, it is pleasing to read his remarks regarding the value of interchange of thought and ideas. To put it in his own words, as stated at the Cinquantenaire " . . . . I became editor of the *Revue de Metallurgie*. The reading of foreign reviews, the correction of proofs and correspondence with readers opened my eyes to a number of problems, and were the starting point of my propaganda in favour of the Taylor system.

" As an example of mutual improvements I remember that after having instructed Osmond in the use of my thermo-electric couples, I learned from him the principles of microscopic metallography.

" The works of Sir W. Roberts-Austen, Director of the Royal Mint in London inspired me with ideas, which are generally accepted to-day, as regards the constitution of alloys.

" It was through the inspiration of Sir Robert Hadfield, the scientific director of Hecla Works, Sheffield, that I took up my researches on optical pyrometry.

" Messrs. H. M. Howe and A. Sauveur, professors of metallurgy in the United States, opened my eyes in the course of continuous correspondence, to the particularly interesting problems in the metallurgy of steel.

" We have continually collaborated in our investigations to such a degree that it has often been difficult to be sure which part has originated with a particular individual.

" Osmond and myself were never able to decide who was the first to compare the transformations of steel with the phenomena of solubility. One day we found ourselves completely in agreement on this point of view after an hour's discussion at the end of which we found that we were left with ideas completely different from those which led up the conversation."

This fine tribute to the value of international co-operation, from so able a scientist, is well worthy of record.

The optimum hardening temperature of an alloy steel should be determined experimentally wherever possible, since the method of manufacture, mechanical treatment, size of section, etc., all influence this temperature. Alloy steels are not so subject to mass effect as carbon steel, i.e. they harden better throughout the mass.

Heat treatment requires knowledge, skill, and judgment for its proper performance. Temperature control should always be by means of pyrometers.* It is not sufficient nowadays to work to such instructions as "Harden at a red heat and temper at a straw colour." The following are important factors in heat treatment which should receive attention—Adaptation of the proper fuel to a furnace; method of heating, including time in furnace, location in furnace, character of furnace gases whether neutral, reducing, or oxidizing; location and correctness of pyrometers; time of transference from the heating furnace to the quenching bath; shape and size of the bath; nature and temperature of the quenching medium.

A study of heat treatment should be attended by the study of the structure and constituents of steel.

During Sir Robert Hadfield's term of office as President of the Faraday Society, an important symposium originated by him was held on the subject of pyrometry (in 1917) when nineteen papers were read, comprising with the discussions 180 pages; see Appendix III.

**Annealing.** Annealing is usually carried out with the object of softening steel, either for the purpose of removing the internal stresses produced by the rapid cooling of large masses or complicated shapes, for undoing the hardening effect of cold work, or for removing hardness arising from rapid cooling or quenching.

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* See also *Pyrometers and Pyrometry*, by Ezer Griffiths, uniform with this volume (Pitman, 2s. 6d. net)

The results produced depend on the maximum temperature reached, the time during which the steel is kept hot and the rate of cooling. The temperature required depends on the nature of the steel and the purpose of the treatment. Usually this temperature lies somewhere about 650° to 800° C. This treatment leads to a " balling up " of the carbide and the destruction of the lamellar pearlite constituent. The mechanical properties of the steel then resemble those of carbon—free iron with an extremely low elastic limit and resistance to fatigue. If the annealing temperature is chosen just above the critical range of the steel, the latter is left in a stronger and more resistant condition. Though this type of treatment is generally known as normalizing, it is sometimes contended that delicate heat treatment is too expensive for use with ordinary steels.

In comparing ordinary steels with alloy steels, it is sometimes thought there is an advantage of simplicity, that the carbon steel as the simpler material, does not require careful heat treatment. Actually, correct heat treatment makes so great a difference even to simple carbon steels, that for many purposes the use of more expensive alloy steels could be avoided if adequate care and skill were devoted to the simpler material.* Great care is given to the question of the chemical composition of steel, and heavy expense is incurred in securing adequate purity, but the steel is sometimes afterwards ruined through lack of care in heat treatment.

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* *See* Appendix I.

# CHAPTER III

## NICKEL STEEL

NICKEL steel may be considered not only as one of the early alloy steels, but also as one of the most important and most abundantly used. Nickel was first isolated by the Swedish mineralogist, Cronstedt, in 1751, but a century or more elapsed before malleable nickel was produced. Nickel steel was first used about 1888, and its qualities and merits were announced in 1889 in a paper read by Mr. James Riley (before the Iron and Steel Institute), who described some of the products and properties of alloys of iron and nickel produced originally in France and then in England. In 1890, a face-hardened (Harveyized) nickel steel armour plate was tried, and in its early days nickel steel was used almost exclusively for armament purposes. Sir Robert Hadfield's paper on the "Alloys of Iron and Nickel,"* read before the Institute of Civil Engineers in 1899, was the first correlated study of this particular alloy steel. Exhaustive work has also been done on nickel iron alloys by the French metallurgists Dumas and Guillaume.

**Manufacture of Nickel Steel.** Nickel steel is made by various processes, open hearth, electric and crucible, and presents no particular difficulties in manufacture. Nickel may be added to the bath at any time, practically without loss or waste, but the addition is usually made just long enough before tapping or pouring to become properly diffused. Nickel is not used as a curative agent, i.e. it cannot deoxidize iron though it is thought to hinder segregation of carbon and other metalloids. It is important that the ingots be sound and free from blowholes or nickel steel may contain seams appearing as dark coloured lines on the metal; rolling at a high temperature has been found to lessen this tendency. The scale formed on nickel steel adheres more firmly to the metal than does that on carbon steel.

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* *See* Appendix II, p. 169, Paper No. 17.

Nickel steel can be forged and rolled without any great precautions. Above 5% nickel, the steel tends to become hard and difficult to work either hot or cold. Steel with 5½% of nickel was found hot-short at 1100° C. Liability to laminated structure or seams can be overcome by care in manufacture and forging.

**Influence of Nickel.** Nickel has a beneficent effect on steel, making the structure finer and more homogeneous, and is pre-eminently a strength-giving element. The useful range of 2% to 40% is wider than that covered by most other alloying elements. Nickel increases the strength, ductility and toughness of carbon steel, also the ratio of the elastic limit to the tensile strength, and renders the steel more susceptible to heat treatment.

**Structure and Classification of Nickel Steels.** When nickel is added to hypoeutectoid steel it dissolves in iron to form an iron-nickel alloy which, on cooling through the critical range, replaces both the free ferrite and pearlitic ferrite of carbon steel. Nickel also has an obstructing influence on the separation of pearlite; the pearlite areas are less distinctly laminated than in carbon steel. Nickel up to about 8% reduces the eutectoid ratio below that of straight carbon steel. The eutectoid composition for 3% nickel contains 0·75% carbon, while for 7% nickel the carbon content is 0·6%. This is of importance in case-hardening work. Nickel steels are classified as follows (Fig. 18)—

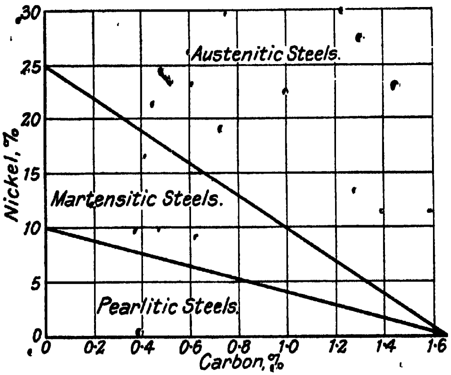

FIG. 18.—CONSTITUTIONAL DIAGRAM OF NICKEL STEELS.

*Pearlitic Nickel Steel* are those which, when cooled slowly, consist wholly or in part of pearlite. The nickel varies from 0 to 10% with the carbon ranging inversely from 1·65% to nil. Hadfield and Guillet showed that pearlitic nickel steels are of the greatest practical importance. They are like carbon steels but superior.

*Martensitic Nickel Steels* contain from 10 to 25%

nickel, and show only a partial transformation from austenite to pearlite on slow cooling. They are like quenched steels, showing high tensile strength, and low elongation and shock. These steels are of little practical interest.

*Austenitic Nickel Steels.* Above 25% the influence of the nickel lowers the transformation range below atmospheric temperature, and the steels are always austenitic, regardless of the carbon content. They show a polyhedral structure characteristic of pure metals and simple solid solutions.

**Heat Treatment and Magnetic Properties of Nickel Steels.** The successful heat treatment of nickel steel requires experience and knowledge. Treatment is based on the position of the change points. Nickel has the property of lowering the critical points of iron to a marked degree. Each 1% of nickel, up to 7%, lowers the $Ac_1$ point approximately 8 to 11° C. and the $Ar_1$ point 17 to 22° C. The $Ar_1$ point of 3·8% nickel steel is from 75° C. to 100° C. lower than that of a corresponding carbon steel, and for a 25% nickel steel it is below atmospheric temperature. The addition of nickel seems to slow up the formation of the solid solution, and therefore a somewhat prolonged heating at the proper quenching temperature is necessary to effect the transformation. The tendency to brittleness due to more or less prolonged heating in excess of the upper critical range is much less in nickel steels than in straight carbon steels. To save time, nickel steels are heated to such temperatures and then cooled down to just above the $Ar_1$ point before quenching. A content of about 8% nickel, near the limit of the pearlitic steels, is the highest useful content amenable to ordinary annealing and quenching operations. The austenitic nickel steels cannot be hardened by quenching. The magnetic properties of nickel steels have been studied by Hopkinson, Barrett, Ewing, Hadfield,

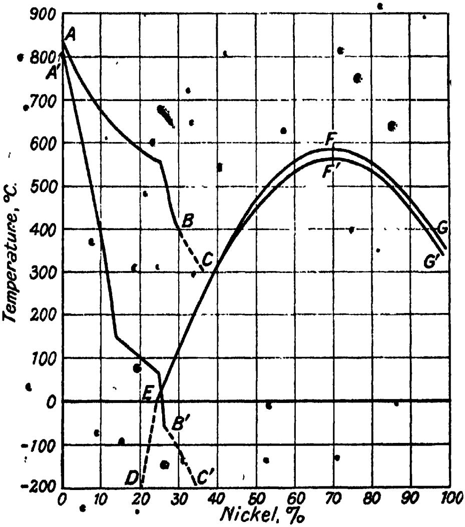

FIG. 19.—MAGNETIC CHANGE POINTS OF NICKEL STEELS.

Osmond, Guillaume, Dumas and others, and show marked peculiarities. Steel containing 25% of nickel is non-magnetic in the ordinary condition, but if cooled to –40° C. it becomes magnetic and retains its magnetic properties on returning to ordinary temperature and does not revert to its original condition until heated to 580–600° C. This type of change is called irreversible, and alloys containing 25% nickel or less belong to this class. Those alloys which lose their magnetic properties on heating and regain them on cooling to the same temperature belong to the reversible class. Steels with over 40% nickel show reversible transformation (Fig. 19). Dr. Hanson has shown that the critical points obtained by means of electrical conductivity measurements agree very closely with those obtained by means of thermal curves and, in investigations by other workers, by magnetic tests. From 12 to 25% of nickel the irreversibility is most marked, and these alloys show the highest strength and elastic limit. The alloys used by the earlier investigators all contained carbon and manganese, which affect the transformation points more than does nickel itself, so that the results obtained are of use only from the point of view of works' practice in the correct treatment of nickel steels. Dumas stated that no nickel iron alloy was non-magnetic at ordinary temperatures except steels containing carbon and manganese. In alloys containing from 27 to 31% of nickel he found both reversible and irreversible transformations and concluded that pure iron-nickel alloys between 20 and 37% of nickel have both. In the nickel alloy containing 30% nickel, the reversible transformation produces a material with low hysteresis loss and low magnetic saturation, while the irreversible transformation gives a material with six times the saturation value but fifteen times the hysteresis loss. On the whole, nickel lowers the ultimate saturation value of iron, but it has been found that a nickel content of 5% to 7% raises the permeability for high inductions by about 5%. This alloy may therefore find a limited application.

**Mechanical Properties of Nickel Steels.** Above a content of 2%, 1% of nickel adds about 2½ tons per sq. in. to the maximum strength as compared with carbon steel, with only slight, if any, decrease in ductility without heat treatment. A nickel content from 3¼ to 3½% gives best results in structural steel. A steel with 3½% nickel and 0·25% carbon has the same tensile strength as a 0·45% carbon steel. Not only is the maximum strength raised (2½ to 3½ tons per 1% of nickel) but the elastic limit is higher than in carbon steels, the elastic ratio being about 60%, as compared with 50% in carbon steels. The resistance to fatigue is also increased to six times the fatigue life in some cases. From 5% up to 8% nickel the hardness is increased but the steel is still amenable to heat treatment. An air-cooled 5 to 6% nickel steel (0·3% C.) showed the following properties—Elastic limit 38 to 45 tons per sq. in.; maximum strength 45 to 50 tons per sq. in.; elongation 25 to 20%; reduction of area 70 to 60%; Izod test 25 to 35 kg. per sq. cm.

Steels containing more than 10% nickel and up to 18% are comparatively hard and brittle, possessing high strength and low elongation, with a limited field of usefulness. The steel referred to by Arnold and Read in 1914, containing 0·55% C. and 13% Ni, has the following properties—Yield point 60 tons per sq. in.; maximum strength 90 tons per sq. in.; elongation 12% in 2 in. Before Arnold & Read's investigations, the steel with 15% nickel was thought to be the strongest of the series, but it can now be surpassed by much cheaper heat-treated ordinary nickel-chromium steel. The high nickel austenitic steels have low elastic limits but high elongation and contraction, also low moduli of elasticity. The modulus of ordinary nickel steel is 29,500,000 lb. per sq. in., but for steel with 20% nickel it is appreciably lower.

The minute crystalline structure of nickel steel causes the development and propagation of cracks to be relatively slow. Nickel steels in general use are somewhat harder than the corresponding straight carbon steels (i.e. with the same percentage of carbon), but they are readily machinable and have a lower coefficient of friction. The hardness of pearlitic nickel steels shows a greater mass effect when quenched in oil than in water, so that test values are incomplete unless the size of section is quoted.

The coefficient of linear expansion of steels with a high percentage of nickel is small (*see* Table III).

### TABLE III

COEFFICIENTS OF LINEAR EXPANSION OF NICKEL STEELS

| Nickel per cent. | Coefficient of Linear Expansion per 1° C. |
|---|---|
| 25 | ·000 018 5 |
| 27 | ·000 011 0 |
| 30 | ·000 005 5 |
| 32 | ·000 003 5 |
| 34 | ·000 002 5 |
| 36 | ·000 001 5 |
| 38 | ·000 000 4 |
| 43 | ·000 005 6 |
| 60 | ·000 016 0 |

The corrodibility of nickel steel is less on the whole than that of carbon steel, unless the carbon be very low, and decreases with the amount of nickel present. Steel containing 30% nickel is used for boiler tubes which last nearly twice as long as mild steel tubes.

Nickel steel is tough under impact and the shearing strength of nickel steel rivets is less likely to be irregular than that of carbon steel rivets.

With regard to their behaviour at low temperatures, Hadfield has shown that nickel steel retains its ductility at the temperature of liquid air. This also applies to the material he discovered known as "Resista," which is a compound alloy of iron, nickel, and manganese.

**Case-Hardening Nickel Steel.** Case-hardening steels are soft and readily machined. By means of carburizing, the hardness of the outside is increased until it may equal that of tool steel, and is thus highly resistant to frictional abrasion. There should be no free cementite in the "case" or a liability to flake arises.

Case-hardened steels are heat-treated as follows— The core is refined by quenching from 900° C. or lower for alloy steels, and the case is then refined and hardened by quenching from a lower temperature. Lower temperatures than for ordinary mild steel are used in heat-treating nickel case-hardening steels owing to the effect of nickel in depressing the change points.

The strength of cases may be considered to be the same for all steels. Beam tests have shown that cracks appear at skin stresses proportional to the maxim strength of the core. The core with the highest yield point will endure the highest stresses.

Impact tests on case-hardened parts are low and seem to be independent of the core material. The addition of nickel in case-hardened steel renders the core less susceptible to brittleness, and gives more uniform results. There is a slight tendency for nickel to resist the penetration of carbon, making the penetration slower than in the case of straight carbon steels, but the graduation is more uniform. The rate of penetration with 5% nickel steel is about half that of plain low-carbon steel. [illegible]% and 5% nickel steels are most generally used for case-hardening. Manganese increases the ability of steel to absorb carbon, but the case tends to be brittle and sensitive to shock, hence this element is kept low. The steel should be kept as free from silicon as possible, and sulphur and phosphorus should also be kept low.

**Uses of Nickel Steel.** The great bulk of simple nickel steel, containing from 2% to 4% of nickel (carbon 0·2 to 0·5%), is used for structural and engineering purposes, i.e. in bridges, machine parts, engines, large dynamos, the frame and engine of automobiles, gun and marine forgings, etc. It is employed for bridges of large span only; for moderate span simple carbon steel is perhaps as good and less costly. Another application is for seamless tubes for bicycles and other high grade tube into which it is cold-drawn. Alloy steel containing 3% of nickel has been used for the steel rings in some large dynamos. Steel rails containing 3½% of nickel have been tried by American and other railroads, but have not shown any marked superiority. Simple nickel steel is also used in marine shafting, railway motor shafts, axles, wire, cable, etc.

Steel with 5% nickel or above (carbon 0·3 to 0·4%) possesses great resistance to shock, and is used for shield plates for field artillery and other bullet-proof plates. Steel with 22% nickel is highly resistant to some types of corrosion, and has been used for valve stems of salt water systems and for the electrodes of sparking plugs. Steel with 24% to 25% nickel meets with some special applications owing to its non-magnetic properties and the fact that it can also be machined. Steels with 28 to 35% nickel are tough and dense, highly resistant to shock, little subject to corrosion, and have low coefficients of expansion (*see* Table III, p. 55); they do not respond to heat treatment, but may be annealed at 690–700° C. for machining. Steel containing 36% to 38% of nickel is known as Invar and, owing to its very small coefficient of expansion, this alloy is used for balance wheels of watches and pendulums of clocks, tape measures, geodetic and similar instruments for precise measurement. With very low carbon, the coefficient for Invar is less than that of any other metal or alloy known. The coefficient is only suppressed over a moderate temperature range (up to 300° C.) but not for contraction at low temperatures. After ageing, Invar becomes practically constant in length. Carbon even in very small quantities has a marked effect on nickel iron alloys and renders them much more liable to undergo changes. Every care is therefore taken, in the manufacture of standards of length, to keep this element as low as possible.

Steel with 46% nickel containing 0·15% carbon, is known as platinite. It has the same coefficient of expansion as platinum and glass, and has been used for the leading-in wires of incandescent lamp bulbs. Steel wire, containing 38% of nickel, copper coated, has since been found better than platinite for this purpose. The nickel steel core expands less than the glass, and the copper case more, and the expansions of the core and case are so balanced that the resultant expansion of the wire is made the same as that of the particular kind of glass to be used. Tubes of steel containing 38% of nickel have been used in marine boilers, and have been found to last three times as long as simple steel tubes.

# CHAPTER IV

## CHROMIUM STEEL*

**Influence of Chromium.** Chromium is pre-eminently a hardening agent, great hardness being conferred on steel by from 1 to 2% of this element. Independently of the carbon content, the hardness increases somewhat with the addition of chromium. Besides being a hardening constituent, chromium raises the critical temperatures on heating, but the effect is not very great, 1% of chromium raising the critical point 30° or 40° C. The transition of hardening carbon to pearlitic carbon is, however, hindered by chromium which retards the decomposition of the solid solution into iron and carbon, especially when present in amount exceeding 3%. Chromium decreases the tendency to crystalline growth, and gives the steel fine or dense grain. Combined with nickel or vanadium, this element gives the strongest and best-wearing commercial steels, which can also be machined easily. Such steels are used for gears from which it is almost impossible to break the teeth, also for crankshafts of internal combustion engines and other parts subjected to heavy service.

**Manufacture of Chromium Steel.** Chromium steel may be made in either the open hearth, electric, or crucible furnace. Broadly speaking, low-carbon chromium steels for case-hardening are made in the open hearth, and high-carbon steels for heat-treating are made in the electric furnace. At the temperature of molten steel, chromium is capable of reducing iron oxides. It may be added—as ferrochrome—any time during melting in the electric furnace, but in the open hearth the practice has been to add just long enough before casting for it to be melted and become well mixed through the charge, care being taken that the slag is not in a strongly oxidizing condition. The ingot moulds must be in good condition and the steel teemed very carefully. Chromium steel is worked by the same methods as carbon steels, but it is always used in the heat-treated condition, toughness being imparted by the fine-grained structure which is characteristic of chromium steel.

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* *See* Appendix II, p. 169, Paper No. 7.

**Structure of Chromium Steels.** While nickel is found in the ferrite, part of the chromium in steel is always found in the form of a carbide. A certain portion of the chromium is soluble in iron, but the amount dissolved never exceeds 30% of the chromium present. Chromium is associated with the cementite and does not react with carbon to the exclusion of iron. The carbide may exist as iron-chromium carbide or as a solution of $Fe_3C$ and $Cr_4C_2$. Iron-chromium cementite is not as readily dissolved or diffused as ordinary cementite on heating, nor does it segregate or separate to form pearlite as readily on cooling. Carbon steel containing over 0·87% carbon contains free carbide of iron enmeshing the crystals and tending to make the steel brittle. When chromium is present, a lower percentage of carbon results in the formation of free carbide. The iron-chromium-carbon system is rather complex, and the double carbides are not of definite composition. The critical temperatures of chromium steel depend on the rate of cooling. The micro-structure of chromium steels are shown diagrammatically in Fig. 20.

When the chromium is above 7% in low-carbon steels, or 5% in high-carbon steels, the steel is composed only of martensite. Heat treatment has little or no influence except to refine the grain. Increasing the chromium above a certain limit fails to produce the austenitic condition. The pearlitic steels are those of greatest usefulness.

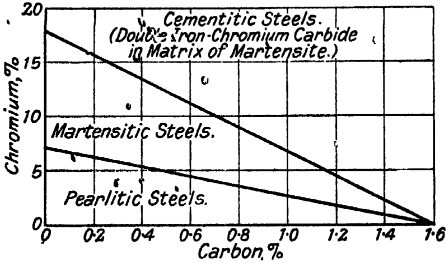

FIG. 20.—CONSTITUTIONAL DIAGRAM OF CHROMIUM STEELS.

**Heat Treatment of Chromium Steels.** Chromium steels are active in response to heat treatment. Chromium intensifies the sensitiveness to quenching and reduces the liability of the steel to fracture. Chromium steels are very sensitive to variation in the temperature from which they are cooled. The amount of undercooling which may occur before the critical change takes place depends on the temperature to which the steel has been heated, and on the proportions of chromium and carbon present in the steel. It has been suggested that the addition of chromium does not result in the lowering of the temperatures of critical changes on cooling if sufficient time is allowed for the decomposition of the solid solutions. If the viscosity of the solid solutions is sufficiently high to prevent the change taking place, the steel is "air hardening." It can, however, be softened by annealing just below the $Ac_1$ point. Chromium widens the tempering range and the steels may be tempered up to 700° C.

**Mechanical Properties of Chromium Steels.** Chromium has little effect on the mechanical properties of annealed steel, but more improvement is effected by heat treatment of chromium than carbon steels. Chromium increases the elastic limit and maximum strength without appreciable loss of ductility. The yield point is 80% or more of the maximum strength if the chromium content is greater than 2%. Chromium also increases the hardness and resistance to shock and alternating stresses. A very wide range of properties may be obtained for any one steel. Although the mechanical properties conferred by chromium are of a high order, the important effect of the carbon content should not be overlooked. 3% chromium steel is a useful composition. 12% chromium steel hardens to 100 tons per sq. in. maximum strength when air-cooled from above 900° C.

In case-hardening steels chromium tends to increase the rate of penetration of carbon and gives a hard case. A small amount of chromium confers greater homogeneity, strength and wearing qualities.

**Uses of Chromium Steels.** Chromium steels are used principally whenever hardness is desired, for example, in projectiles, stamp shoes and dies for crushing hard ores, in drawing-dies, etc.; their high elastic limit is an additional factor which makes them suitable for crushing machinery. In America, chromium steel is used in three- and five-ply plates, i.e. welded together alternately with wrought iron for burglar-proof plates. High quality files are made of 1·3% carbon and 0·5% chromium steel. Chisels and impact tools, axes and hammer heads are also made of low chromium steel, the latter sometimes containing from 0·3 to 0·7% carbon and from 0·6 to 0·9% chromium. Chains and track bolts are sometimes made of chromium steel with low carbon content (0·3%). Chromium steel is used for balls and rolls for bearings, ball races, etc., on account of its high resistance to wear and abrasion. The steel previously employed for ball bearings was carbon steel case-hardened. The steel now favoured contains approximately 0·8 to 1·0% carbon and 1·2 to 1·6% chromium, and may have a maximum strength of 130 tons per sq. in. Balls of less than ½ in. diameter are usually hardened by quenching in water from about 775° C., and larger balls from about 800° C. The balls may be tempered at 200° C. without reducing the hardness but the toughness is improved and strains due to quenching are released. Balls of ¾ in. diameter, tested by the 3-ball method, should withstand 50,000 lb., the pressure over the area of contact being then greater than 1,000,000 lb. per sq. in. It is the double carbides in chromium steel which increase the resistance to wear.

The suitability of chromium steel for magnets was indicated by Professor Brown of Dublin, in 1909, who examined a range of steels, made by Hadfields, Ltd., containing 0·75 to 9·5% chromium. They had high coercive force (*see* Fig. 30, p. 104) but no advantage was obtained by adding more than 2½% to 3% of chromium. Professor Brown found that a steel containing 0·86% carbon and 1·95% chromium made the best chromium steel magnet. The war brought a tungsten famine, and in Germany the use of chromium steel was resuscitated in 1917, as it was found that with careful treatment good magnets are obtained. They do not, however, come up to tungsten steel magnets in quality and are still more inferior to cobalt steel magnets (p. 111).

Steel containing 20% of chromium is very resistant to acid corrosion. Steel highly resistant to corrosion containing about 12% chromium is considered below. Steels containing from 7 to 8% chromium resist scaling, and such scale as does form is particularly adherent and affords a certain amount of protection against further attack.

Steel containing 40% chromium and a little molybdenum can be boiled in salt and citric acid, and be heated to from 800 to 1100° C. for an indefinite time without scaling.

**Rustless (Chromium) Steel.** In view of the importance of the metal chromium in its many applications —which include iron chromium alloys for the production of armour plates, projectiles, axles, tyres, springs, motor-car and aeroplane steels, rustless steel, articles to resist wear and tear, and for many other purposes—it may be of interest to trace briefly its history and its uses.

Chromium was first discovered by Vauquelin, the French Chemist, in 1797, during the stormy days of the Republic. Then Berthier, Fremy, Boussingault, carried out laboratory and other experiments. In England, Faraday made experiments on iron alloyed with chromium in 1820. In 1869, Julius Baur, at Brooklyn (N.Y.) carried out many investigations and made some practical applications of chromium steel, but the first introduction of the steel for use in industrial purposes was probably due to Brustlein of the Holtzer Company, who paid special attention to this particular alloy steel. Brustlein commenced his experiments in France in 1875, and his firm, Holtzer, first supplied chromium steel for industrial purposes in 1877.

Brustlein's able work was recognized in France by the Société d'Encouragement pour l'Industrie Nationale, who awarded him in 1903 a prize of 2,000 francs for his work on this type of steel.

Notwithstanding the work done by those mentioned, however, no correlated data or systematic research had been presented as to the effect of chromium alloyed with iron in varying percentages either in this country or elsewhere, until Sir Robert Hadfield's paper on " Alloys of Iron and Chromium " was read before the Iron and Steel Institute in 1892. Between 1890 and 1892 Hadfield made a series of alloys of iron and chromium varying from 0·22% up to 16·74% Cr., comprising a range of 15 alloys. In seven of these alloys the carbon present amounted to 0·21% or under ; in five of them the carbon content was from 0·40% to 1·00% ; and in the remaining three there was from 1·27% to 2·12% carbon.

Detailed information was given in this paper concerning the method of manufacture, composition, forging, heat treatment, mechanical and physical tests, micro structure, and other particulars. In this paper, too, the subject of the corrosion of chromium steel, now so important a matter, was first taken up. Hadfield proved clearly that high chromium steel—for example, specimen " L " mentioned in the paper, containing 9·18% Cr.—was quickly corroded or eaten away by sulphuric acid. He was therefore, the first to show that alloys of iron with high percentages of chromium would be of no value under this particular type of test, and in practice this has proved to be the case. This was therefore, a specific and practical fact regarding corrosion, knowledge of which afterwards proved of considerable help in the development of the steel.

Accompanying this same paper to the Iron and Steel Institute was the valuable report by the great French metallurgist, Professor Floris Osmond, who was an intimate friend of Sir Robert Hadfield's, in which the following statements were made with regard to the two specimens " J " and " L "—

As regards Specimen 1176 J, 0·77% C.; 0·50% Si.; 5·19% Cr.; " This metal is characterized by the presence of a number of small white points of great hardness and brilliancy, which are scarcely at all attacked by the acid, as shown by the photograph. These white points, which we found to be still more numerous in sample " L," appear to be a compound of iron, chromium, and carbon. The matrix has the structure of hardened steel, and is entirely composed of simple cells of about 0·001 mm. diameter. The photograph shows the white points well, also the fact that composite structure is absent."

Concerning Specimen 1176 L, 0·71% C.; 0·36% Si.; 9·18% Cr.: "As regards the specimen annealed at 1320° C., the amount of chromium is much higher than in " J," and the transformation of the matrix into hard metal 'little capable of being reacted upon by acids' and no longer showing the reaction of hardening carbon, is almost complete. The etching with nitric acid may be continued as long as two minutes without sensibly altering the appearance of the sample."

The same facts also apply to the three steels—

Specimen 1176 M. 1·27% C; 0·38% Si; 11·13% Cr;
" 1176 N. 1·79% C; 0·61% Si; 15·12% Cr;
" 1176 O. 2·12% C; 1·20% Si; 16·74% Cr.

It will be seen that the above specimen L, and the three steels M, N, O, were all forerunners of the present rustless steels.

In his conclusions regarding the chromium steel alloys mentioned, Osmond stated that as the amount of chromium increased, a compound of iron, chromium and carbon appeared to be formed, which was only partly attacked by acids and possessed great hardness.

It will thus be seen that as a result of the researches of Hadfield and Osmond important information was obtained in the development of chromium steel of various types, including steel of a composition not very dissimilar to that now used and known as rustless steel. In mentioning this early work it is not with any desire to detract from the excellent work of several later investigators. As regards corrosion qualities, the facts set forth by Hadfield and Osmond, who worked together in the matter, were certainly the earliest records demonstrating that the resistance of chromium iron alloys varies with the nature of the attacking acids. Such steel was not further developed at the time because it was then most difficult to obtain suitable chromium or ferro-chromium of the required low carbon type, at any rate at prices which would enable industrial products to be manufactured.

The characteristics of the present non-rusting chromium steel are the product of many minds and much research. Sir Robert Hadfield in his introductory address at the symposium on "The Corrosion of Metals; Ferrous and Non-Ferrous," also in his contribution to the discussion on his paper entitled "The Corrosion of Ferrous Metals," read before the Inst. of Civil Engineers on 4th April, 1922, pointed out that full credit should be given to Messrs. Thos. Firth & Sons, Mr. H. Brearley, and Dr. W. H. Hatfield, for the work they had done in developing chromium steel possessing high rust-resisting qualities.

In a paper entitled "Stainless Steels" read before the Midland Institute of Mining, Civil, and Mechanical Engineers on 8th April, 1922, Dr. Hatfield stated that it was in "1912-1913 that Mr. Harry Brearley discovered that the 12% to 14% chromium steels, when in the hardened condition, resisted successfully general atmospheric and many other active influences which lead to corrosion."

It has been pointed out by Dr. Aitchison and others that rustless steel is not one steel but a group of steels. They are generally made in the electric furnace, but with proper care can also be made successfully in the open hearth. The percentage of chromium lies between 11% and 15%, and the carbon content is usually less than 0·45%. If the carbon is lowered the chromium may be lowered too. Silicon gives a cleaner and sounder metal and neutralizes the effect of carbon, but it is kept less than 0·3%; manganese is less than 0·5%, and sulphur and phosphorus are kept as low as possible. A little nickel is sometimes present, but it possesses no beneficial effect. If the cutting properties are of subsidiary interest, the carbon may be as low as 0·15 to 0·20%. As mentioned above, chromium has the effect of lowering the eutectoid composition of steel to a considerable extent. With 12% chromium, the eutectoid occurs at 0·3% carbon and this steel consists almost entirely of pearlite. It is only this amount of carbon which goes into solution at the Ac point, 800–830° C., the rest of the carbide dissolving progressively over a range of about 200° C. The sulphur present seems to be in solid solution. The Ar point occurs at about 750° C., but the steel possesses marked air-hardening properties. High-carbon stainless steel is austenitic and rather soft, but not machinable. It becomes hard when stressed or tempered.

**Mechanical Treatment of Rustless Steel.** Great care is required in the mechanical treatment of rustless steel owing to its air-hardening properties. When the carbon is less than 0·2%, the steel is easily forged under the hammer; if the carbon lies between 0·2 and 0·4% the steel can only be forged into simple shapes; and when the carbon exceeds 0·4% the steel is difficult to forge. Above 0·5% carbon, the steel has great strength at high temperatures. The forging temperature is usually about 1000° C. Forging begins at 1150° C., and should not be continued below 900° C., in fact, the temperature range 900 to 850° C. is to be avoided. If the steel is forged below 830° C. it will be cold-worked. After forging or rolling, the steel should be cooled slowly in the range 800 to 600° C. to enable the carbon change to take place so that the steel may become soft.

Rustless steel may be drop-stamped between 1200 and 1000° C.; any flashes formed should be removed while hot.

**Heat Treatment of Rustless Steel.** When the carbon content exceeds 0·25%, rustless steel possesses the useful property of air-hardening, this capacity increasing with the temperature to which the metal is heated. With free cooling from 900° C., a ball hardness of 500 is attained. The air-hardening property induces a lessened tendency to cracks, warping and soft spots but requires care in the course of manufacture. The steel may also be hardened by quenching in oil or water from 920° C., the choice of hardening medium depending on the section under treatment and the hardness desired. Properly hardened rustless steel has a martensitic structure with globules of the double iron-chromium carbide. To soften rustless steel for machining, filing and chipping it is annealed at 700 to 750° C. In treating this steel the use of a salt bath is

TABLE IV

TEMPER COLOURS OF RUSTLESS STEEL

| Temperature, ° C. | Temper Colours. |
|---|---|
| 300 | Straw |
| 350 | Brownish straw |
| 400 | Brownish purple |
| 450 | Bluish purple |
| 500 | Reddish purple |
| 550 | Purple blue |
| 600 | Light blue |
| 650 | Bluish violet |
| 700 | Greyish violet |
| 750 | Grey |

advisable, and temperatures should be controlled by pyrometer. As a matter of interest, the temper colours of rustless steel are given in Table IV, as they are not the same as those of carbon steel.

**Mechanical Properties of Rustless Steel.** The range of tensile strength obtainable varies with the carbon content approximately as follows—

| *Carbon.* | *Tensile Strength.* |
|---|---|
| 0·1 to 0·2 | 40 to 80 |
| 0·2 to 0·3 | 45 to 90 |
| 0·3 to 0·4 | 50 to 105 |

Hardened in air from 950° C. or in oil from 920° C. and preferably tempered at 200° C., a tensile strength of 100 tons per sq. in. is obtained (*see* Fig. 21). For engineering purposes the steel is generally hardened in oil by quenching from 900° to 920° C. and tempering at 650° to 750° C.; the mechanical properties shown in Table V are then obtained—

### TABLE V

MECHANICAL PROPERTIES OF RUSTLESS STEEL, AS USED FOR ENGINEERING PURPOSES

Yield Point, 30–55 tons per sq. in.
Maximum Strength, 45–65 tons per sq. in.
Elongation, 28–15%.
Reduction of Area, 65–35%.
Izod Test, 70–25 ft.-lbs.

In tempering, there is not much change in tensile properties between 650° and 750° C., and therefore very great care is not necessary. Up to 500° C., the toughness increases without much fall in hardness, but the ball hardness drops considerably in the range 575° to 650° C. There is a drop in the Izod test on tempering at 500° C., indicating a tendency to brittleness at this temperature. The coefficient of expansion of rustless steel is 0·000 010 9 per 1° C.

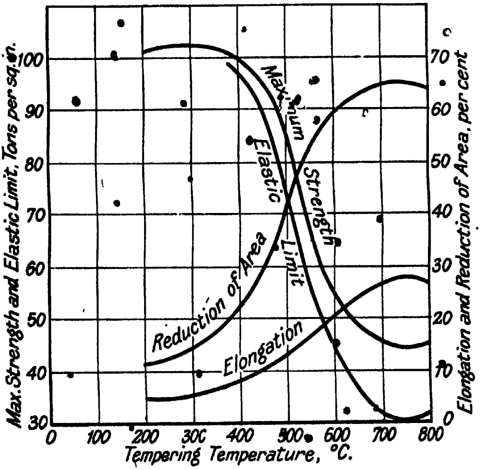

FIG. 21.—MECHANICAL PROPERTIES OF RUSTLESS STEEL. Carbon 0·30% ; chromium 12% ; air-hardened.

**Resistance to Corrosion.** Rustless steel is practically unaffected by moisture, fresh and salt water and such organic acids as occur in fruits. It is not affected by vinegar unless tempered to 700° C. Rustless steel is resistant to strong or weak nitric acid and concentrated or dilute solutions of ammonia whether cold or boiling. It is not resistant to sulphuric acid and caustic alkalis. It may be etched by a mixture of concentrated hydrochloric and nitric acids, or by a saturated solution of ferric chloride in hydrochloric acid.

The way in which the material is heat-treated affects its non-rusting properties. Maximum resistance to corrosion occurs in the hardened condition, but it is not much diminished by tempering up to 700° C. The resistance to corrosion is not merely skin deep but the surface should be smooth with a good polish and free from strained parts. If the material is scratched, torn or distorted, it has been cold worked to some extent, and this is detrimental. Special care and attention should be given to grinding rustless steel. High-carbon steels (with more than 0·5% carbon) are more subject to corrosion than low-carbon steels.

Rustless steel does not scale appreciably up to 800°–850° C. It is twenty-five times more resistant to scaling (as measured by loss in weight after exposure for a definite period to oxidizing conditions at high temperatures) than is ordinary carbon steel. It is also better in this respect than 25% nickel steel and high-speed steel; consequently it has met with some application for aeroplane engine valves and similar purposes. In addition its strength, and to some extent its hardness, are well retained at these high temperatures.

When the chromium content is increased to 14-18% and from 2-4% of silicon is added the steel is stated to be rustless in the untreated condition. In addition to being made into cutlery this material is also used for valves and similar parts which must resist scaling.

**Applications of Rustless Steel.** The commercial utilization of the non-corrosive properties of high chromium steel has been regarded as one of the outstanding events of the last decade in the metallurgical world. It has been applied to all classes of cutlery, including razors and surgical instruments. It can be drawn into wire and stamped into dishes. It may soon be of general use in the workshop, and its application to docks, ship construction, and bridges would offer great advantages. Rustless steel has recently been tried in the form of turbine blades. Experiments carried out by Dr. W. Hatfield, Messrs. Thomas Firth and the British Thomson Houston Co., at both the high and low pressure ends of a turbine, demonstrated that rustless steel blades were practically untouched while the standard 5% nickel steel blades were corroded in the usual way. The mechanical properties of the two materials were as in Table VI.

TABLE VI

NICKEL STEEL AND CHROMIUM STEEL FOR TURBINE BLADES

| | 12% Chromium Steel. | 5% Nickel Steel. |
|---|---|---|
| Yield Point, tons per sq. in. . . . | 44 | 25 |
| Maximum Strength, tons per sq. in. . | 54 | 55 |
| Elongation, % . . . . . . . | 20 | 31 |
| Reduction of Area, % . . . . . | 60 | 61 |
| Ball Hardness . . . . . . . . | 255 | 150 |

In a hydraulic pump, a rustless steel ram wa only worn one-seventh as much as the non-ferrou rams.

In this connection, trials may be mentioned whic have been made by Sir Robert Hadfield on forged pump rams made of rustless chromium steel, at the Hecla Works, Sheffield, under conditions such that frequent observations could be made of the behaviour of the steel. The conditions under which the tests were made were somewhat severe, the water passing through the pump in a circulating system, and becoming very muddy owing to the iron oxide resulting from the corrosion of the pipes. Rams of ordinary steel were found unsuitable, due to rapid rusting and pitting, and ordinarily phosphor bronze rams were used. After two years' service these were very much worn and had to be machined to a smaller diameter; they then lasted for a similar period before being discarded. The ram of rustless steel was examined after being used for a period of eighteen months, and from the point of view of corrosion, it was found to be in perfect condition, except for a few slight pit marks; the amount of wear was only 0·01 in. on the diameter. The results have fully justified the use of this steel for such purposes, even though its cost is higher than that of ordinary steel.

An interesting application of rustless chromium steel during the war was its use to resist the severe corrosive influences to which certain naval constructions were exposed. As an example there may be mentioned the diaphragms used in connection with submarine work, of which large numbers have been made of "Galahad" non-rusting steel at the Hadfield Works in Sheffield. These diaphragms are used for taking up vibrations in hydrophones, and considerable difficulty had been experienced with such parts of submarines. After exhaustive tests the rustless steel described above quickly proved its superiority; in addition to withstanding sea water attack, the acoustic properties of this steel proved to be superior, for example, to those of high nickel steel, which is fairly resistant to corrosion. The acoustic qualities depend on the hardness and the elastic limit of the material, which properties are quite high in the case of the rustless steel. It may be mentioned that these rustless steel diaphragms after being immersed in sea water under service conditions for six months, were found to be in practically the same condition as when first fitted. The actual loss of metal due to corrosion during the period of immersion was practically nil—a remarkable testimony to the non-rusting quality of this material.

**Rustless Iron.** Rustless iron is really rustless steel containing about 0·1% carbon. Soon after rustless steel was first manufactured it was found that rustless iron could be produced by much the same process except for the use of a smaller quantity of carbon-free ferro-chrome. As this essential product in its manufacture is expensive, rustless iron is more costly than rustless steel. Ordinary ferro-chrome contains from 5 to 9% carbon.

Rustless iron is usually made in the electric furnace. It is softer than rustless steel and readily forgeable; from four to six times as much forging can be done in one heat as on rustless steel. It can be tempered, its maximum strength varying from 70 to 30 tons per sq. in. according to the heat-treatment given. Because of its malleability, it has a wider range of use in forging, pressing and drop stamping than rustless steel, and is more readily machined. A useful application is in the production of sheets for motor-car hoods, wheel discs, etc., and its use is in contemplation for motor car bodies and in replacing nickel plated parts and other products subject to corrosion or tarnishing, thus eliminating painting and varnishing. It is expected in some quarters that rustless iron will modify the light metal industry in the future. Although it is more expensive than brass, it can be kept clean more easily. The mechanical properties of rustless iron make it suitable for the production of intricate drop forgings, weldless drawn tubes, strip and wire which may be made up into door mats, spring mattresses, necklaces, watch chains, etc. It is used for the production of golf clubs, kitchen utensils, shop signs, door plates, etc., and may be used for the furnishings of railway carriages, engines and rolling stock generally.

Spoons and forks made of this alloy take an excellent polish, slightly darker than but closely resembling silver, and withstanding wear and tear much better than the latter. Rustless iron sheets with a high polish are also used for mirrors,

# CHAPTER V

## SILICON STEEL

**Effect of Silicon.** Silicon is soluble in iron in quantities up to 15%, and has a double effect. Part of it combines with the iron and remains in solid solution during cooling of the alloy, while a smaller part reduces the iron oxide present. Silicon is a powerful deoxidizer, and has a tendency to remove gases and oxides from steel, thus preventing the formation of blowholes and giving the steel greater soundness and toughness. It is about four times as active as manganese, but excess beyond about 4% makes the steel hard to forge and roll. Silicon is detrimental to welding if the carbon-content is high. The first additions of silicon to steel produce no effect on the microstructure except to increase the grain size. With 2% silicon, the grain becomes quite coarse and cannot be altered except by considerable mechanical working. If the silicon content is increased to 5%, the carbon present may be partly carbide and partly graphite, but the whole can be precipitated as graphite. With more than 7% silicon, the graphite is embedded in a ground mass consisting of the solid solution of FeSi in iron. Carbon in the form of graphite has a much less damaging effect on the magnetic properties of iron than in the dissolved state or in the form of cementite. (*See* also Sir Robert Hadfield's paper on the Alloys of Iron and Silicon, Appendix II (2), No. 4.)

Silicon steels are generally made in the acid open-hearth furnace. The silicon must be added to the bath only a short time before teeming as the metal is readily oxidized. Owing to the short time available, the silicon is usually added by means of ferro-silicon or specially high silicon alloys while hot or in the

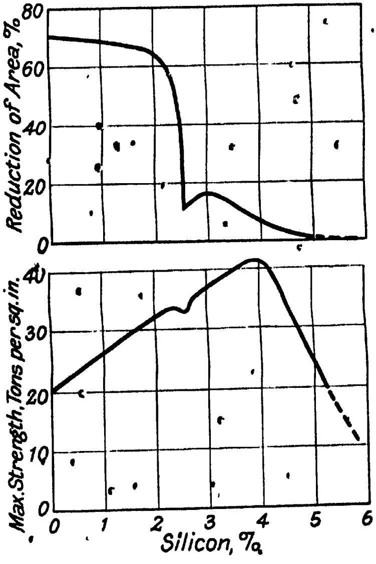

FIG. 22.—MECHANICAL PROPERTIES OF ANNEALED SILICON STEELS.

molten state. Care should be taken in rolling silicon steels as they are liable to be cracked by heavy reductions.

**Mechanical Properties of Silicon Steels.** The strength of iron is increased slightly by the addition of silicon in proportion to the amount added up to about 4%. Up to 2% or rather more the elastic limit is raised without appreciably impairing the ductility, and 3½% silicon steel though quite stiff can be bent at right angles. With 4% silicon and above, the elongation and reduction of area are nil and the alloys are quite brittle. The maximum strength also decreases when the silicon-content exceeds 4% (Fig. 22). This may be due to the formation of graphite, and the yield coincides with the breaking point. Alloys of iron with more than about 5% of silicon are not forgeable. Unlike carbon, silicon does not confer upon iron the property of becoming hardened when quenched in water. Silicon steel has low resistance to impact which is not indicated by the usual tensile test; it also shows marked weakness when broken transverse to the direction of working. As the silicon increases it is more difficult to stamp the steel in the form of sheets. The magnetic properties of silicon steel are discussed below; in practice an economic balance is struck between the mechanical properties, the magnetic properties and the cost.

**Magnetic Properties of Silicon Steels.** Between 1895 and 1900 Sir Robert Hadfield made a large number of alloy steels, and with the collaboration of Sir William Barrett, investigated their magnetic properties. The results published in 1900-02 showed that the only two which appeared to be of commercial value were the iron-aluminium and the iron-silicon alloys, both produced by Sir Robert Hadfield. On account of the much lower cost and the greater ease and uniformity with which the silicon alloys could be made, efforts were concentrated on these, The 2½% silicon steel, rolled into sheets, had 25% higher maximum permeability and a hysteresis loss two-thirds that of pure iron. The electrical resistance was also increased at the rate of 10 to 12 microhms per cm.-cube for each 1 per cent of silicon added; this is an advantage as it reduces the eddy-currents loss.

After overcoming many difficulties this remarkable discovery eventually led to the adoption of the Hadfield material in transformers and electrical machinery. The performance of transformers, in particular, depends on the characteristics of the iron used in their construction. At the beginning of the present century the best transformer sheets were made of Swedish charcoal iron having a maximum permeability of about 4,000, and a hysteresis loss of 3,000 ergs per cu. cm. per cycle. A type of mild steel, known as "Lohys," was made by Messrs. Sankey, and possessed a maximum permeability of 3,800 and a hysteresis loss of about 3,000 ergs per cu. cm. per cycle, the maximum induction being 10,000 gauss and the frequency 60 cycles per sec.

The ageing properties of these materials were such that, in many cases, the losses increased to double or more in a few months, necessitating dismantling the transformer and annealing the iron sheets. The Hadfield low-hysteresis steel, however, shows no ageing, in fact, the material usually improves with service (*see* Fig. 24). In addition to the higher permeability than iron for magnetic forces below saturation, the coercive force and retentivity were reduced to nearly half those of standard iron.

Messrs. Sankey, who acquired the Hadfield patents, have produced very large quantities of this material under the trade term "Stalloy."

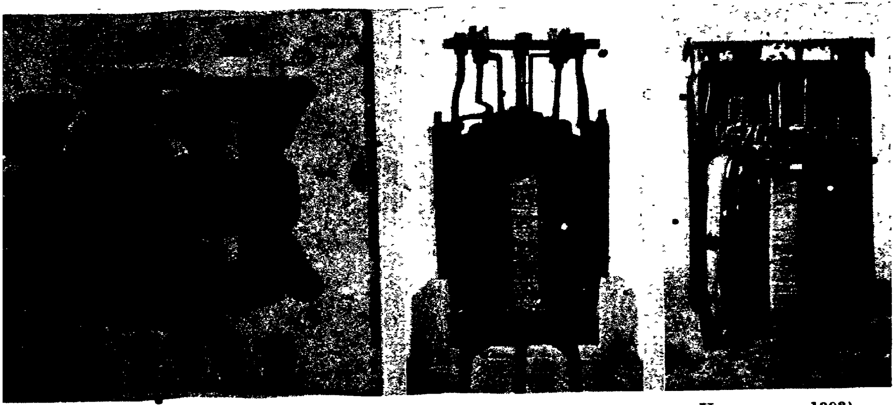

Fig. 23.—The First Transformer Using Low-Hysteresis Steel (made by Hadfield in 1903), also 20 kW and 60 kW Transformers made in 1905 and 1906 Respectively.

In America the licensees were The United States Steel Corporation, through their subsidiary companies the American Sheet and Tin Plate Company, the General Electric Company, the Westinghouse Electric and Manufacturing Company, also the American Rolling Mill Company.

It is not often that an invention can be followed in detail from its source, but in this case it is easy to do so. The first transformer made by Hadfield of his low-hysteresis steel was built in 1903 and, weighing only about 20 lb., was really a laboratory apparatus. The success of this experiment was so great that immediately afterwards the Sheffield Corporation made two further transformers of the Hadfield low-hysteresis material, of 40 and 60 kW capacity. These have been running ever since 1905 and 1906 respectively, and the material in them, when tested in September, 1921, was found to be of even higher efficiency than when first put to work, that is there has been no ageing or diminution of quality, but on the contrary an improvement. These three transformers are shown in Fig. 23.

This material has been found of immense benefit to users of electrical machinery in which the maintenance of low hysteresis loss is of primary importance. It has been estimated that the total saving effected in coal alone has already reached 50,000,000 tons. In addition to this, there are the resulting advantages and economies which the new material has made it possible to effect in the design and construction, also the saving in copper in transformers, dynamos and other electrical apparatus.

The results of this invention are emphasized because they show how "from small beginnings great things spring." Thus from a small experiment, costing but a few pounds, the present day large scale application of the Hadfield low-hysteresis material

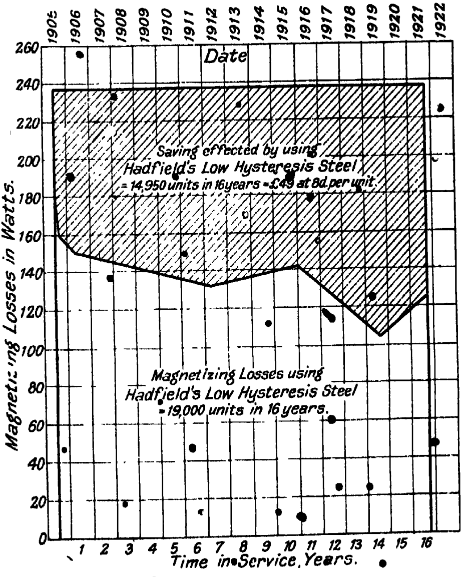

FIG. 24.—DIAGRAM SHOWING SAVING IN ELECTRICAL ENERGY DUE TO THE USE OF LOW-HYSTERESIS STEEL IN THE 40 kw TRANSFORMER ILLUSTRATED IN FIG. 23.

has evolved. Of such magnitude has it become—and it will be still greater during the next ten years—that in 1921 Dr. Yensen, in estimating the total saving to the world during the first seventeen years after the introduction of the Hadfield low-hysteresis steel, calculated that it amounted to the immense sum of 340 million dollars which he said " would be nearly enough to build the Panama Canal."

Fig. 24 shows the continual saving in energy consumption effected by the use of low-hysteresis material in the 40 kW transformer mentioned above. The actual saving would in point of fact be greater than the figures shown as, in comparing the magnetizing losses with those of transformer iron, the well-known ageing qualities of the latter material have been neglected.

The remarkable magnetic properties of silicon steel are brought out by a double heat treatment which consists in annealing the sheets at 1070° to 1100° C. for several hours and cooling quickly, then reheating to 750° C. and cooling slowly, although a single treatment at about 800-850% is sometimes employed. Annealing decomposes the cementite ($Fe_3C$) but the temperature is not carried high enough for the carbon to pass into solution. The steel should contain the smallest possible amounts of carbon, manganese, and other impurities. Increase in grain size increases the eddy-current losses and permeability, at least in low and medium fields.

Transformers of the Hadfield silicon steel were first made in the United States in 1906, and in 1910 Dr. Morton C. Lloyd calculated that this steel was saving that country about ten million dollars worth of electrical energy per annum.

Due to the improvements effected in manufacturing processes and the use of better raw materials, it is now possible to make the 4% silicon alloy with an energy loss slightly greater than 1 watt per kilogram, instead of 1·8 watts per kilogram* obtained when the material was first produced, and the permeability may be increased to 8,000. It has also been shown that the material can be still further improved by special methods (*see* Table VII).

In 1915, Dr. Trygve D. Yensen, of the Westinghouse Laboratory, published his results on iron-silicon alloys melted in vacuo. The crystal size was much greater than in the less pure alloys, and the ductility was greater due to the absence of carbon. The limit of forgeability of these special vacuum alloys was 7 to 8% silicon, but a brittle range occurred at 2·5 to 2·6%. The tensile strength of the 4·5% alloy attained 52 tons per sq. in. As regards magnetic qualities the best alloys contained 0·15 and 3·4% silicon respectively and, after annealing at 1100° C., showed hysteresis losses one-half and one-third of those of the corresponding commercial alloys. With refined methods of preparation and vacuum heat treatment, these alloys have a maximum permeability of 40,000 or higher, and a hysteresis loss of 300 ergs per cu. cm. per cycle (for $B_{max}$ = 10,000 gauss). Bars of commercial silicon steel in which the carbon has been reduced to less than 0·01%, by annealing under oxidizing conditions, have also shown these superior properties.

**High Silicon Alloys.** Steels of high silicon-content are used on account of their high resistance to chemical action, e.g. as containers for sulphuric acid. Commercial alloys, like "Duriron" and "Tantiron" (Table VIII), and "Ironac," contain

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* With maximum induction 10,000 gauss and at 60 cycles per sec. in both cases.

## TABLE VII

### THE DEVELOPMENT OF LOW-HYSTERESIS STEEL

| Year. | Material. | Investigator | Maximum Permeability. | Max. Induction = 10,000 gauss. | | Electrical Resistance. Microhms per cm.-cube. |
|---|---|---|---|---|---|---|
| | | | | Coercive Force. Gilberts per cm. | Hysteresis Loss. Ergs per cu. cm. per cycle | |
| 1900 | Swedish Charcoal Iron | Hadfield | 4,000 | 0·92 | 3,000 | 10·2 |
| 1903 | 3·5% Si Alloy . . . | ,, | 5,100 | 0·72 | 2,300 | 60 |
| — | 3% ,, . . . | ,, | 7,000 | 0·70 | — | 48 |
| — | 3·75% ,, . . . | ,, | — | — | 775 | 57 |
| 1912 | 1·75% ,, . . . | Paglianti | — | 0·6 | 1,650 | — |
| 1913 | Vacuum Iron . . . | Yensen | 19.000 | 0·25 | 813 | 9·85 |
| 1915 | 0·15% Si Alloy * . . | ,, | 66,500 | 0·09 | 286 | 11·8 |
| ,, | 3·4 % ,, * . . | ,, | 63,300 | 0·08 | 282 | 48·5 |
| 1916 | 3·0 % ,, * . . | ,, | 72,000 | 0·09 | 254 | — |

* Melted *in vacuo*.

about 14% silicon, but experiment has shown that over 20% silicon (corresponding to $Fe_2Si$) must be used if the highest resistance to corrosion is to be secured. Unfortunately these high silicon ferro-silicons are fragile.

Tantiron is used for towers for concentrating acids, and Ironac principally for tubes and fittings used in the manufacture of nitric acid. "Corros-iron" is another high-silicon alloy also resistant to corrosion and rusting.

TABLE VIII

COMPOSITION AND STRENGTH OF DURIRON AND TANTIRON

| | Duriron. | Tantiron. |
|---|---|---|
| Silicon . . . . | 14–14·5 % | 14–15 |
| Carbon . . . . | 0·2 – 0·6 % | 0·75–1·25% (graphite) |
| Sulphur. . . . | 0·01– 0·05% | 0·05–0·15% |
| Phosphorus. . . | 0·16– 0·20% | 0·05–0·10% |
| Manganese . . . | 0·25– 0·35% | 2·00–2·50% |
| Tensile Strength . | ¾ that of cast iron | 6 to 7 times that of cast iron |

M. S. W. Parr published in America the data given in Table IX, illustrating the high resistance of ferro-silicon to attack by 25% nitric acid.

**Other Uses of Silicon Steels.** During the Great War use was made of quaternary silicon-nickel steel, the nickel being present in about the customary amount used in nickel-chromium steels. These steels are not easily made, but if carefully prepared and suitably treated they combine high strength with considerable toughness, and possess high resistance to impact, making them in some respects suitable for bullet-proof plates and similar purposes.

### TABLE IX

#### RESISTANCE OF VARIOUS METALS TO 25% NITRIC ACID

| Metal. | Percentage Dissolved in 24 hrs. |
|---|---|
| Pure Iron . . . . . | 100 |
| Aluminium (commercial) . . . | 51 |
| Monel Metal . . . . . | 19 |
| Nichrome (90/10) . . . | 8 |
| Copper-Aluminium (90/10) . . | 3·5 |
| Ferro-Silicon . . . . | 0·1 |

Mild steel containing 0·25% Si has been used in several American bridges as it can be rolled into sections of lighter weight which, however, possess the same strength as the heavier mild steel sections. This type of steel was used in the construction of the *Lusitania* and *Mauretania.*

Silicon steel (3 to 4% silicon) is employed for telephone diaphragms as sounds of the same intensity can be produced with considerable saving of electrical energy. Silicon steel of an average composition—carbon 0·5%, silicon 1½ to 2%—is sometimes used for springs. In spring steel of this type, the manganese-content is usually higher than in ordinary steels, being generally about 1·5 to 2%, hence these alloys are usually known as silico-manganese steels.

# CHAPTER VI

## MANGANESE STEEL

THE first systematic investigation of alloys of iron and manganese was made by Sir Robert Hadfield in 1882, when he invented the steel which carries his name. He showed that by increasing the manganese content beyond about 2½% the steel became seriously embrittled—this was partly known—and he further showed that by increasing the manganese content above 7% an entirely new metal was produced, the alloy containing 12 to 13% manganese possessing greater hardness and toughness than had previously been supposed possible in one alloy steel. This complete research was the first of its kind, and from it the modern field of alloy steel research has developed. The various papers by Hadfield on manganese steel are shown in Appendix II (1).

The original castings of manganese steel produced by Hadfield, which were first exhibited in 1887 on the occasion of his paper read before the Institution of Civil Engineers, are shown in Fig. 25. Additional applications of manganese steel at an early date are shown in Fig. 26, which photograph was taken in 1892.

**Influence of Manganese.** Manganese is an element always found in steel, 80% ferro-manganese being usually added to the steel at the time of tapping or in the ladle, in order that oxygen may be absorbed

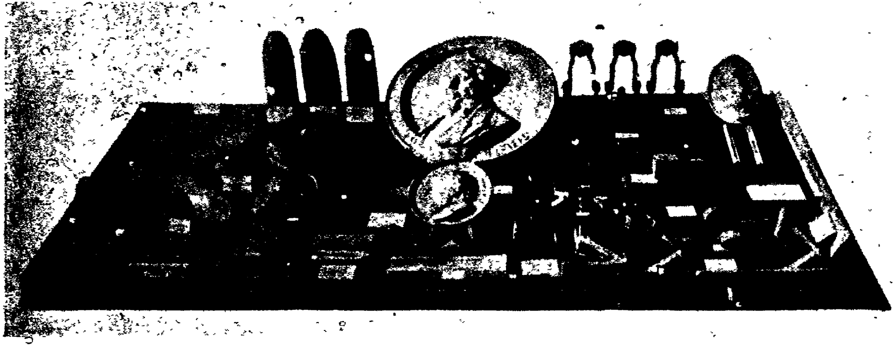

FIG. 25.—ORIGINAL CASTINGS OF MANGANESE STEEL AS EXHIBITED BEFORE THE INSTITUTION OF CIVIL ENGINEERS IN 1887.

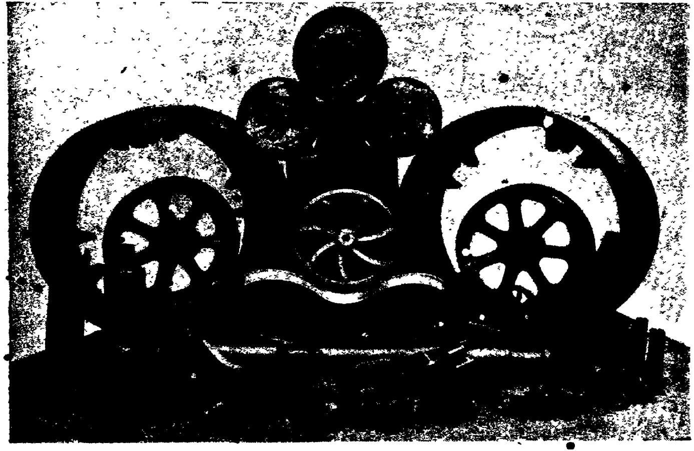

FIG. 26.—EARLY MANGANESE STEEL CASTINGS AND FORGINGS EXHIBITED BY SIR ROBERT HADFIELD IN 1892.

from the bath and transferred to the slag as oxide of manganese. Manganese also prevents the coarse crystallization which sulphur and other impurities tend to induce. The maximum temperature to which it is safe to heat steel during manufacture and subsequent treatment is raised by manganese which resists separation of the crystals on cooling and confers the quality of "hot ductility" on the steel. In other words, manganese prevents "red shortness" and adds toughness to the finished product.

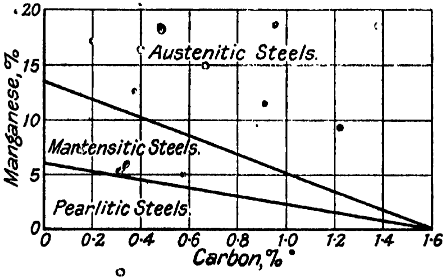

FIG. 27.—CONSTITUTIONAL DIAGRAM OF MANGANESE STEELS.

Manganese destroys the magnetic susceptibility of iron, about 16% of the element rendering the iron virtually non-magnetic. When carbon is present, as in commercial manganese steel, a non-magnetic alloy is obtained with a smaller percentage of manganese.

Another property of manganese is its tendency to increase the stability of air-hardening steels.

The constitutional diagram of manganese steels is shown in Fig. 27. The alloys of commercial value are the austenitic steel containing 11 to 14% manganese and 1·2 to 1·3% carbon, and to a lesser degree the pearlitic manganese steels containing up to 3% manganese. The term "manganese steel," however, conveys to the mind of the average man connected with the metallurgical industry the alloy containing about 1·3% carbon and 13% manganese. This invention of Hadfield manganese steel was the first industrial application of steel containing such high percentages of the alloying element.

**Pearlitic or Low-Manganese Steels.** Above 0·5% of manganese, the strength of carbon steel is increased without the elongation being much diminished. From 1 to 3% of manganese imparts a higher and better-defined elastic limit, but the ductility begins to fall. In addition, the manganese increases the dynamic strength and gives a greater margin of hardening temperature. Thousands of axles and tyres are made annually containing 1% manganese. In the United States, steel containing 0·8% carbon and 2·0% manganese, after receiving proper heat treatment, has been employed for shear blades for the cold cutting of steel. A steel containing 0·35% carbon and 1·50% manganese was found to have properties equivalent to those of 3½% nickel steel with the same carbon content.

**Manganese Steel.** If the manganese in steel is increased above about 3% (or about 2% if the carbon is high) the steel becomes increasingly brittle, so much so that steel containing 4 to 5½% manganese can be powdered under the hammer. Above 7% manganese, however, an entirely new set of properties begins to appear, and the brittleness gradually disappears; the strength and ductility return and reach a maximum at about 14% manganese. Commercial manganese steel has approximately the composition: Carbon 1·0 to 1·3%, silicon 0·3%, sulphur and phosphorus 0·05 to 0·08%, manganese 11 to 14%. Its properties are the opposite of those which might reasonably have been expected on logical grounds, and demonstrate the fact that because a given amount of an element produces a certain effect, it does not follow that a different amount will give the same effect in a different degree. It should be added that the full toughness of manganese steel is not obtained until it has been toughened by what is called the water-quenching method, which again marks out manganese steel as being an entirely new product in ferrous metallurgy.

**Manufacture of Manganese Steel.** Manganese steel is made in the ladle from a mixture of decarburized iron (not over 0·1% carbon) and 80% ferro-manganese melted separately in crucibles or in a cupola furnace. The decarburized iron used should not be too hot or the steel will contain blowholes. If the steel is to be cast into ingots, it should stand a little so that the silicates formed may float to the top. The oxidation losses generally amount to 1½%. The ladles are generally clay (acid) lined. The fusible and liquid slag formed is green in colour from the silicate of manganese which is absorbed. Coffee-pot ladles are sometimes used to facilitate skimming the slag. The chief production of manganese steel is for castings but it is also forged and rolled into rails. Unlimited difficulties were encountered in the early stages of its manufacture and heat treatment.

**Heat Treatment of Manganese Steel.** Manganese steel must be heated very slowly and uniformly. Forging is performed in a narrow range of temperatures above red heat, beginning with light taps of the hammer. As cast (Fig. 8, p. 18), or if the ingots are slowly cooled, manganese steel is brittle. The effect of quenching is to soften and toughen the steel giving it an austenitic microstructure, the carbon being completely in solution. The manganiferous austenite is unstable; separation of carbides begins about 400° C., and reabsorption by the austenite ends about 930° C., the liberation on cooling being at about 735° C. Quenched from about 1000° C. in water, the material is as ductile as wrought iron, but the maximum strength is three times as great. Manganese steel cannot be softened by heating followed by slow cooling. The thickness of sections employed is limited by the necessities of the drastic quenching treatment. There is an almost complete absence of critical points. The composition of manganese steel is important but the heat treatment is more so. No time must be lost in bringing the articles up to the quenching temperature and transferring them to the water bath.

**Mechanical Properties of Manganese Steel.** Manganese steel possesses the characteristic properties of austenite—low elastic limit, low hardness, good tensile strength and elongation, high resistance to shock and lack of magnetic qualities. After water quenching from 1000° C. the tensile strength is 60 to 70 tons per sq. in. (Fig. 28) with an elongation of 50 to 70% on 3 in. The contraction of area is fairly uniform over the whole parallel portion of the test piece. Owing to the low elastic limit, the elastic ratio is only about 35%. The Brinell hardness is 200 to 220, but the material cannot be machined and must be ground to shape. For this reason, wheels, pulleys, etc., of manganese steels are provided with mild steel bushes cast into the articles. The specific gravity of manganese steel is 7·89 or about

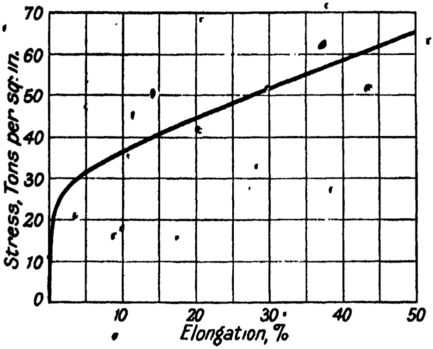

FIG. 28.—STRESS-STRAIN DIAGRAM FOR MANGANESE STEEL.
C. 1·20% ; Mn. 12·5%.)

the same as that of simple steels with the same carbon content. The specific heat is 0·145 at atmospheric temperature. The thermal expansion is 50% greater than that of iron. The shrinkage in cooling from casting temperature is $\frac{5}{16}$ in. per foot. The electrical resistance is 71 microhms per cm.-cube, or about eight times that of pure iron. The thermal conductivity is one-sixth that of iron.

The non-magnetic properties of manganese steel are remarkable, as shown by E. Hopkinson, Barrett, Ewing, Hadfield, Osmond, Guillaume, Dumas, and others. Although this alloy contains 86% or more of iron, its magnetic susceptibility is very low ($19 \times 10^{-6}$). Heating to 500° to 550° C. for several hours increases the specific magnetism to 50% that of pure iron. At the same time the steel is made hard (450 to 500 ball hardness) but is machinable. Double carbides of iron and manganese —$Mn_3C$ and $Fe_3C$—are deposited in acicular formation. These hard and brittle carbides effectively break up the continuity of the tough matrix. They are redissolved at 670°C.

Manganese steel hardens under pressure and resists deformation and wear. For this reason it is specially suitable for parts subjected to abrasion such as jaws of stone and ore crushers, pins and links. It is also used largely for dredger buckets, tramway and railway switches and crossings, rails in curves, and mining car wheels. The suggestion has been made to insert manganese steel rails in the ordinary track at positions where it is customary for trains to stop and start.

**Applications of Manganese Steel.** Although the uses of manganese steel are somewhat limited by the fact that machining and cutting to shape are practically impossible, over 1½ million tons of this material have been produced. It may be interesting to note the large monetary saving which has accrued to the world from the invention of this steel. Estimating the probable saving at £20 per ton, there has been up to date a total saving of about £30,000,000.

Owing to the high tenacity of elongation of manganese steel, it met with an important war application in the manufacture of shrapnel-proof helmets and body guards, which saved tens of thousands of lives ; over 7 million of these Hadfield manganese steel helmets were supplied to the Allies' troops. On account of its non-magnetic properties it was used in the construction of mines, the presence of which could not be detected by magnetic means.

Manganese steel has also been employed in the construction of burglar-proof vaults, and for armoured and other structures near the magnetic compass on ships and aeroplanes.

# CHAPTER VII

## TUNGSTEN STEEL*

**Effect of Tungsten.** Tungsten has a hardening effect on steel, somewhat similar to but less than that of chromium, and it has also a much smaller efficiency in increasing the depth of penetration of carbon in case-hardening or carburizing operations. Tungsten steel shows a characteristic fine-grained, silky or porcelanic fracture when properly heat-treated. The German metallurgist, Mars, concluded that tungsten lowers the melting point of iron, but there is some doubt as to the correctness of this statement. The specific gravity of steel increases perceptibly with the tungsten content, the specific gravity of tungsten being 19·3.

Pure iron can dissolve as much as 9% of tungsten without any excess forming tungstide ($Fe_2W$). If carbon be present, a part forms tungsten carbide (WC) and more tungsten is required to form iron tungstide in proportion as the carbon content increases. The tungsten carbide forms under normal conditions the double carbide with cementite, which dissociates above $Ac_1$ into the simple carbides; if the heating is not carried too high, the simple carbides reassociate on cooling. If heated to a higher temperature the tungsten carbide reacts with some of the iron to form the tungstide and a certain proportion of cementite. It is the formation and dissolution of the tungstide in austenite which causes the lowering of the transformation temperature on cooling. The carbides of tungsten are complex and there is evidence of $W_3C$, $W_2C$ and WC forming at high temperature. Honda and Murakami in their work on the constitution of tungsten steels recognize the existence of the following constituents—

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* *See* Appendix II, p. 169, Paper No. 25.

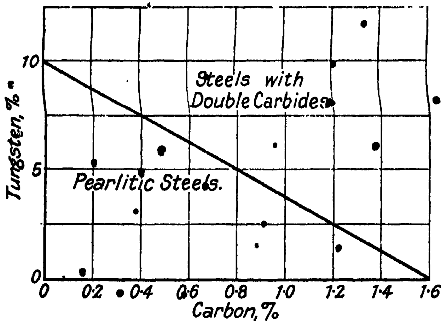

FIG. 29.—CONSTITUTIONAL DIAGRAM OF TUNGSTEN STEELS.

ferrite, $4Fe_3C{\cdot}WC$, $Fe_3C$, WC and $Fe_2W$. The constitutional diagram of tungsten steels is given in Fig. 29.

**Manufacture and Properties of Tungsten Steel.** Tungsten steel is preferably manufactured by the crucible process, the tungsten being placed on top of the material which is packed cold in the crucible, in which the steel is melted and killed. Tungsten does not remove oxides and gases. The steel is usually cast into 3 in. square ingots, and is forged or rolled like high-carbon steel, great care being employed in bringing the steel up to the working temperature.

The heat treatment of tungsten steel exerts a considerable influence on the strength, which is considerably improved by the quenching operation. Though without much influence at first the addition of tungsten, up to 10%, increases the yield point and maximum strength of carbon steel with only slight diminution in elongation. The researches of Professors Arnold and Read showed that for low percentages of tungsten the carbon is combined with the iron, but when the tungsten reaches 11½% all the carbon is combined with it.

Carbide steels show lower tensile strength than the corresponding pearlitic steels. Quenching above 850° C. leads to dissolution of double carbides, and results in the formation of a fine-grained martensitic structure.

Tungsten steels not containing high carbon have low thermal conductivity, and tungsten increases the magnetic retentivity of high carbon steel (*see* Fig. 30) though the reason why tungsten steel makes a good permanent magnet is not well understood. Madame Curie first investigated the magnetic properties of tungsten steel and showed that the best composition was about 0·6% carbon and 5 to 6% tungsten. Prior to 1910 high carbon steel (1 to 1·5%) was used for magnets, but since that date several thousand tons of tungsten steel have been produced annually for the purpose. At one time it was thought that small amounts of vanadium, chromium, and molybdenum imparted greater retentivity but this has not been confirmed. Tungsten steel magnets should be forged with as little work as possible. They are heat-treated by soaking at about 850° C. and quenching in water. No advantage is obtained by tempering. The magnets are magnetized by insertion in a long insulated coil through which an electric current is passed, and are then seasoned at 100° C (maturing, ageing). Decay of the magnetic properties may be caused by mechanical shock, changes of temperature and exposure to demagnetizing forces. The magnetism of a newly made magnet is made up of a permanent and a sub-permanent or removable part. The limit to demagnetization and the time taken depend on the type of steel and the dimensions of the magnet.

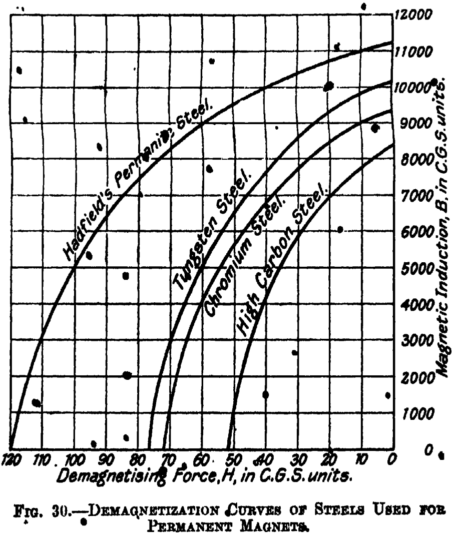

FIG. 30.—DEMAGNETIZATION CURVES OF STEELS USED FOR PERMANENT MAGNETS.

**Uses of Tungsten Steel.** Tool steels containing from 1 to 4% of tungsten are used for finishing cuts on iron and steel. They are capable of machining 35- to 40-ton steel at a speed of 40 ft. per min. A finishing steel for rifle barrels contained 1·2% carbon and 3 to 6% tungsten, and had a keen cutting edge. A further application of tungsten, i.e. as the alloying element present in greatest quantity in high speed steel, is discussed on pp. 133–143.

Tungsten has been used in gun tubes to raise the strength and increase the resistance of the bores to erosion. Steels have been used for howitzer tubes containing 1 and 3% tungsten with 0·[illegible] to 0·7% carbon. Tungsten improves the wearing properties of some classes of chisel steel, a high grade having the composition 1% carbon and 1 to 2% tungsten. Poppet valves in petrol engines are sometimes made of steel containing 0·5 to 0·6% carbon and 1·5 to 2·0% tungsten. Low tungsten steel (0·75%) has also been used for springs. A steel containing 8 to 9% tungsten and about 0·6% carbon was found to make good hot-drawing and pressing mandrels. Tungsten is used in the production of " self-hardening " steels, i.e. those which require no quenching after forging.

# CHAPTER VIII

## OTHER TERNARY STEELS

**Copper Steel.*** At one time copper was thought to produce red-shortness and to make steel unweldable but, in 1899, A. L. Colby made a series of forging and tensile tests on a propellor shaft made of 0·5% copper steel which gave satisfactory results. The material was also welded satisfactorily, and could be flanged cold. The conclusion was reached that the supposed deleterious effects of copper did not actually occur, at least up to 1% of copper. This was confirmed by Dr. Stead and others. Copper steel is generally made by alloying copper with normal open-hearth or Bessemer steel. Copper affects the critical points in the same way as nickel but to a less degree. The mechanical properties of copper steel are somewhat better than those of carbon steel, though unless the copper is above 0·5% its influence is not pronounced. As forged or annealed 0·1% copper adds about ½ ton per sq. in. to the maximum strength of low-carbon steel or ¼ ton to that of medium-carbon steel. In the heat-treated condition, the increase in strength due to the addition of copper is much greater—by adding 0·8% copper to a 0·35% carbon steel the maximum strength was increased 32 tons per sq. in. without the elongation being much affected.

The addition of more than 4% of copper makes steel red-short.

**Resistance to Corrosion of Copper Steel.** Although there are many references in metallurgical literature from the beginning of the seventeenth century to the effect of copper on the physical properties of steel, it is not mentioned until 1900 in connection with the control of corrosion. There has been considerable controversy as to the anti-corrosive effect of the presence of small quantities of copper in steel, but it appears established that even small amounts of copper cause steel to resist certain types of corrosion better than steel not containing this element.[*] The results obtained depend on the actual corrosive conditions. The American Sheet and Tin Plate Company states that 0·15 to 0·25% of copper in sheets preserves them from atmospheric corrosion, so that they last from three to five times as long as similar sheets without copper. They claim that the protective effect was manifested with as low a content as 0·03% copper. Tests were also made by the Lake Erie Railroad on 0·4% copper bearing sheets used in steel railway cars put into service in 1914. After two years' service, the paint was found to have adhered better than on plain carbon steels, and on re-examination after seven years' service, the loss in thickness due to corrosion was much greater in the carbon steel sheets than in the copper steel sheets. Dr. A. S. Cushman, of Washington, D.C., the Scientific Adviser to the American Rolling Mill Company, has done excellent work in studying this subject of corrosion generally. He has found, however, that specially purified "Armco" iron, containing only about ·15% impurities gives, under certain conditions of corrosive action, superior resistance to that obtained with copper steel. His wide researches and many papers on this subject are of the highest value.

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* *See* Appendix II, p. 169, Paper No. 26.

Copper steel specimens containing over 0·1% Cu.

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[*] *See* Appendix II, p. 173, Paper No. 135.

have been found in good condition after having been exposed to atmospheric corrosion for 15 years.

In addition to resisting atmospheric corrosion, copper steel has shown superior results in the alternately wet and dry test. It is also resistant to attack by 20% sulphuric acid, though acid tests have no bearing on natural corrosion due to causes other than sulphurous atmospheres. On the other hand, it is more attacked than pure iron by acid salt solutions and by some neutral and alkaline solutions. Also, copper steel is less effective than pure iron in resisting corrosion by natural waters.

**Vanadium Steel.*** Vanadium is considered to be a deoxidizing agent of considerable power and is supposed to get rid of oxygen and nitrogen, also to increase the molecular cohesion and tend to impart a finer and denser structure than that possessed by ordinary carbon steel. Vanadium promotes the even distribution of carbon and prevents constitutional segregation. The element has a high melting point (1750° C.), and it is very difficult to alloy it with steel in the ordinary plant. It is preferable to add it as 35% ferro-vanadium after the other ladle additions. Ferro-vanadium is sometimes added to the bath two or three minutes after the manganese used for recarburizing, and always under reducing conditions. The ferro alloy, which should contain from 25 to 35% or even more vanadium may be added in the crucible.

Vanadium is an elusive element and it does not follow that a certain quantity added to a heat of steel can afterwards be analysed as present in the steel. With experience, however, vanadium can be added consistently, the loss not exceeding 0·07 to

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* *See* Appendix II, p. 169, Paper No. 26

0·10%. Vanadium has a beneficial effect in open-hearth practice, and the steel is forged without difficulty, but should be worked a little tenderly at first. The temperature should not be too high, and if the steel is worked below a black heat it becomes brittle.

As regards the constitution of vanadium steels, the element dissolves in the ferrite and also exists as a carbide or double carbide with the cementite. All steels above 1% vanadium are cementitic.

Though vanadium is used by some steelmakers, there are various opinions as to its advantages for alloying with steel. From 0·15 to 0·25% is sufficient to affect considerably the physical properties of the steel, and may raise the elastic limit and maximum strength of mild carbon steel as much as 50% without appreciably reducing the elongation and reduction of area. Adding 1% of vanadium raises the elastic limit of pure iron about 10 tons per sq. in., and the ultimate strength about 6 tons. Vanadium increases the toughness of low and medium carbon steel by its solid solution with the ferrite. It prevents brittleness of high carbon steel (0·6 to 0·9% C.) and reduces the tendency to crack during quenching. In other words, it gives a wider safe-hardening range. Properly heat-treated vanadium steel (containing up to 2%) has a reduced susceptibility to sudden shocks and resists fatigue or deterioration under continuous vibration. As the element acts in the same way as carbon, the latter must be controlled carefully in vanadium steel.

Straight vanadium steels have not much standing at present, but they may be said to be in their infancy and progress in their metallurgy and extension in their employment may be expected. They possess the advantage of welding readily, and one grade is used as a flux in oxy-acetylene, oxy-hydrogen and electric welding. On account of their strength and the light construction which they make possible, they are used for springs and axle frames of automobiles, and for shafts, rotating parts and case-hardened gears. Carbon-vanadium tool steel has been used successfully for punching and blanking dies, cold-drawing and forming dies, shear blades, piercing and drawing punches, etc. Vanadium is used in steel castings and cast iron as well as in steel mill products. It is claimed that the element makes chilled cast iron rolls more durable and more ductile.

**Cobalt Steel.** Sir Robert Hadfield in 1891 was the first to investigate cobalt steels systematically, a full account of these experiments appearing in 1904 (*see* Appendix II (2)). He showed that cobalt, like nickel, increases the elastic limit and maximum strength. For certain parts of electrical machinery, such as armature teeth and pole tips, there is needed a material having high permeability at high flux densities. The best material available is the purest iron, but if the saturation value could be raised the length of the armature, for example, could be decreased proportionally, and a large saving would result in the cost of the machine. The researches of Dr. P. Weiss of Zurich, in 1912, showed that the iron-cobalt alloy corresponding to the proportions $Fe_2Co$ (34·5% cobalt) has a saturation value from 10 to 13% greater than that of pure iron. Dr. T. D. Yensen has subsequently found that at high inductions the permeability of the $Fe_2Co$ alloy may be as much as 25% higher than that of pure iron. Unfortunately, the cost of cobalt is high and militates against the use of this alloy.

There has also been invented a cobalt steel, called Permanite, made by Messrs. Hadfield of Sheffield, the magnetic properties of which are far in advance of those of the best tungsten steel for permanent magnets. The coercive force is as high as 120 and the remanent magnetism over 11,000 c.g.s. units (*see* Fig. 30). The high coercive force enables it to withstand rough usage in a remarkable manner, and the steel shows practically no ageing qualities. In the demagnetization curve the product B × H (induction × magnetizing force) has a maximum value of 600,000 as compared with 300,000 for tungsten magnet steel. Permanite is advantageous for use in magnetos and in other applications where demagnetizing influences are high. A strong field is necessary to magnetize this cobalt steel, a magnetizing force of 900 to 1000 c.g.s. units being used.

Professor Honda has recently brought out a steel containing about 35% of cobalt as the principal constituent, which is a great improvement over ordinary magnet steel, but on account of the high proportion of cobalt in its composition is very expensive. It is called K.S. magnet steel after Baron K. Sumitomo. The steel is hard and difficult to work, and should be hardened by quenching in oil from 1000°–1100° C. It is initially magnetized in a field of high strength. It has a coercive force of 180 c.g.s. units as compared with about 75 for tungsten steel of 50 for carbon steel. The remanent magnetism is not diminished by prolonged immersion in boiling water, and exhaustive dropping tests only diminished the magnetization by 6%.

The steel is suitable for short magnets. It has an exceptionally fine microstructure, and the ball hardness varies from 444 to 652.

The addition of cobalt to high speed steel is mentioned in Chapter XI.

**Molybdenum Steel.** In 1904 the well-known French metallurgist, Professor Guillet, contributed a paper to the Société d'Encouragement pour l'Industrie Nationale showing the results of his investigation into the effect of the addition of molybdenum, up to 9·3%, on the properties of iron. Guillet came to the conclusion that the effect of molybdenum was about four times as great as that of the metal tungsten. Unfortunately, Prof. Guillet's specimens contained a considerable percentage of carbon and manganese, so that Sir Robert Hadfield's various researches on this subject including those in 1907* were probably the first systematic investigation of practically carbon-free iron-molybdenum alloys. The materials employed by Hadfield consisted of two series differentiated by the method in which the molybdenum was added, namely (*a*) as ferro-molybdenum or (*b*) molybdenum in the metallic form. In the alloys made with metallic molybdenum, the carbon was constant throughout at 0·10%. The series of iron-molybdenum alloys was composed of fifteen specimens ranging from 0·24% up to a maximum percentage of 23·75% of molybdenum. Tests were made on the alloys in the cast and forged materials, in the unannealed and annealed conditions, and brought out in a remarkable manner the superiority of the forged material. The original cast structures were brittle and were not found to be easily modified by annealing. When the material had been forged, however, great improvement was noticed; although the elastic limit was not much affected, the elongation and reduction of area were excellent.

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* Appendix II, p. 169, No. 76.

In summing up the results Hadfield thought that the effect of molybdenum on iron—that is, on a practically carbonless iron alloy without the presence of other elements—is not likely to be of importance. Its influence, however, may be found very useful in alloys containing higher percentages of carbon. On the other hand, molybdenum renders steel so sensitive to hardening that the material may crack during quenching or spontaneous fracture may subsequently occur.

Molybdenum steel is made in either the crucible, basic open-hearth, or electric furnace, being added either as 45% to 60% low-carbon ferro-molybdenum or 35% calcium molybdate, though the former is to be preferred. In some cases, molybdenum steel scrap may be used. In the crucible ferro-molybdenum is added in coarse lumps; in open-hearth practice it is added in the furnace after the slag has been cleared up. In the latter furnace, the loss amounts to from 5 to 10%, but in the electric furnace the loss is negligible. Molybdenum oxidizes readily, and the oxide easily dissolves in the metal. The steel should be deoxidized with titanium and vanadium. There is no serious difficulty in rolling or cold-drawing molybdenum steel, which shows great freedom from seams. Chromium molybdenum steel flows easily in the dies on forging and is readily machinable.

Molybdenum has a tendency to volatilize at high temperatures and lack of uniformity may arise in molybdenum steel after prolonged or excessive heating.

The chief value of molybdenum lies in indirect or intensifying effect on the more complex steels. It extends the range of hot working and heat treatment and increases the penetrative effect of hardening. In tempering also, the drawing range is widened and the drawing temperature does not require to be controlled so accurately. The effect of molybdenum on the mechanical properties is to increase the elastic limit and elastic ratio, but it exerts most influence on the reduction of area and raises the ductility and toughness of the steel. It increases the tensile strength of carbon and nickel steels. A steel containing 1% of molybdenum and 0·2% carbon after quenching at 910° C. showed improved impact tests, or higher tensile strength for a given impact test. Molybdenum seems to increase the property of deep hardening of chromium steel.

Data concerning the mechanical properties of molybdenum steels are given in Table X.

In America, molybdenum steels have been applied to various uses in aeroplane and automobile construction and for general engineering purposes. Chromium-molybdenum steel has been made into satisfactory springs. Nickel-chromium-molybdenum

TABLE X

MECHANICAL PROPERTIES OF MOLYBDENUM STEELS

| | Steel containing 0·27% C. 0·83% Cr. 0·42% Mo. | Molybdenum Gear Steel. | |
|---|---|---|---|
| Hardened at . . . | 870° C. | — | — |
| Drawn at or to . . . | 320 ball hardness | 200° C. | 540° C. |
| Elastic limit, tons/sq. in. . | 63 | 135 | 85 |
| Max. stress, tons/sq. in. . | 73 | 150 | 90 |
| Elongation, % . . . | 17 | 10 | 15 |
| Reduction of Area, % . . | 63 | 22 | 50 |

steel was used in the Liberty motor for aircraft service. Molybdenum steels were also used for 0·5in. bullet-proof plates for French baby tanks and for military aeroplane construction.

**Aluminium Steel.** Aluminium is not usually added to iron with the object of forming an alloy, but on account of its deoxidizing properties. Dissolved oxide in liquid steel tends to induce the formation of blowholes. As aluminium has a great affinity for oxygen at high temperatures, it tends to reduce the oxides and prevent the violent evolution of carbon monoxide and other occluded gases. The alumina formed is, however, infusible and does not tend to rise into the slag. The element has the additional effect of increasing the solubility of gases in the metal. A small amount of aluminium is usually added in the ladle, but too much kills the steel. Aluminium steels were first investigated thoroughly by Sir Robert Hadfield, who read an important paper on this subject before the Iron and Steel Institute in 1890.* With steel containing 0·2% of carbon, aluminium may be added up to 5% without affecting the tensile strength, but the steel becomes brittle under shock above 2% aluminium. The malleability of the alloys practically ceases at 5·5% aluminium. The hardness is not increased by the addition of aluminium, and water-quenching does not seem to affect the alloys, though if carbon is present the ordinary action takes place. Aluminium appears to cause a precipitation of graphite. The element was found to have an action similar to that of silicon in increasing the intensity of magnetization of iron in low fields, but the alloys are more difficult to make and less regular, for which reason the development of the silicon alloys received more attention.

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* *See* Appendix II, p. 169, Paper No. 6.

Iron and aluminium form an intermetallic compound and the alloy containing 17% aluminium is said to be non-magnetic and rust-resisting. Recently a 15% iron-aluminium alloy has been used for crucibles exposed to high temperatures on account of its resistance to sealing.

**Titanium Steel.**[*] Titanium alloys with iron in all proportions. Up to 9% it has been found to have little effect in improving the mechanical properties. Titanium steel, properly speaking, is not made commercially at present. In 1907 titanium was first applied as a physic in molten steel used in the manufacture of rails. It is held by some metallurgists to be the best all-round deoxidizer, eliminating gases, especially nitrogen, and tending to remove all oxides and slag enclosures. It is next to aluminium in the prevention of blow holes, and is claimed to make steel tougher and stronger. Titanium will not save a bad open-hearth heat, but is useful in reducing silicates and in further purification. Titanium-treated steel is used for plates and sheets owing to its freedom from surface defects and greater ductility in bending without cracking.

**Uranium Steel.** Uranium steels have only recently been developed, chiefly in America. Hypo-eutectoid steels containing less than 0·6% of uranium are pearlitic, but an increase in the content of uranium produces a characteristic constituent which becomes coloured when hot like a carbide of uranium. At the present time, it is not known whether this is a true double carbide or a mixture of carbides of iron and uranium. Uranium has little direct effect on the transformation points up to 2%. Above this the Ar. transformations are lowered and appreciably weakened, even for ordinary cooling velocities. The steels of which the transformation points are lowered have a martensitic structure. If these points are suppressed the structure is polyhedral.

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[*] *See* Appendix II, p. 169, Paper No. 26.

Above 1% uranium the pearlite is no longer lamellar. Quenched uranium steels often contain white crystals which: (*a*) do not become coloured by heat like uranium carbide; (*b*) do not exist in the annealed metal; (*c*) are not attacked by *aqua regia*; (*d*) are associated with the carbide in steels containing more than 0·6% of uranium.

Uranium does not need to be intensified by the addition of other elements. It increases the hardening power of steel in response to water quenching without increasing the fragility. As regards its effect on carbon steel, experiment has shown at 0·22% uranium is comparable with 0·95% of chromium or molybdenum. Uranium steel is reported to be suitable for ordnance and armour, but no definite proofs have been produced.

Uranium increases the hardness of carbon steel on quenching, decreases the grain size, and raises the elastic limit. Steels containing carbon and uranium are principally suited for applications which need a low tempering temperature, for they then exhibit a remarkable hardness, breaking strength and ductility.

The addition of small quantities of uranium in nickel steels increases the hardness after quenching. By adding 0·6% of uranium to pearlitic nickel steels, the grain size decreases and the pearlite becomes more sorbitic.

In general, nickel-uranium steels differ from pearlitic nickel steels in that : (*a*) they have a higher elastic limit for the same ductility ; (*b*) they are harder than the nickel steels after treatment ; (*c*) they are more easily hardened ; nickel-uranium steels harden considerably on cooling in air ; (*d*) they possess a higher fatigue resistance after suitable treatment.

Uranium has been used in high speed steel on account of its tendency to promote the formation of complex carbides. It also assists in the development of secondary hardness in these steels.

**Zirconium Steels.** During the war, a steel containing zirconium was tried in America in armour and bullet-proof plates and for use in motor-car steel. The results were reported to be successful, but the use of this steel does not seem to have been continued. Nickel-zirconium alloys have been tried for high-speed cutting tools, but no sufficient advantages have been brought forward.

Zirconium,* like titanium and aluminium, acts primarily as a scavenger and, when it is not removed as part of the slag, remains in the steel in the form of square bright yellow inclusions not directly visible at magnifications lower than 500 ×. It is not considered that these inclusions can be very beneficial, and if they are segregated and rolled out into thin plate-like streaks they may be detrimental, especially in armour plate.

**Tin Steels.** From an investigation of low and high carbon steels containing from 1·75% up to 10% of tin, Guillet concludes that tin imparts a mineralogical hardness and high fragility to steel, making it difficult to forge. It enters into solution in the iron and appears to enter into combination with it. In tin-steels in which the tin does not exceed 10%, the carbon is in the pearlitic condition. Tin-steels are somewhat like titanium steels in this respect. Tin appreciably retards the progress of cementation.

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* U.S. Bureau of Standard Notes (April, 1922).

# CHAPTER IX

## NICKEL-CHROMIUM STEEL

THE influence of nickel and chromium when combined gives the best all-round alloy steel in commercial use, and we are largely indebted to French research for its rapid development. In addition to being perhaps the most important of the structural alloy steels, nickel-chromium steel is encroaching on the realms of other alloy steels. The presence of the two elements tends to neutralize the harmful effects of each and to magnify the good points. A certain ratio of chromium to nickel (about 1 : 2½) seems to give the most efficient combination of physical properties; if this proportion of chromium is exceeded the temperature limits of treatment are narrowed. This steel is usually made in types containing 1·5%, 2·5% and 3·5% nickel. A material containing 0·6 to 0·7% chromium and 1·25 to 1·5% nickel is used for medium-stressed parts, and 1·1 to 1·25% chromium with 2·5 to 3% nickel is employed for highly stressed parts. Nickel-chromium steels are usually heat-treated, and possess the highest physical properties of any steel known. Nearly all the useful steels are in the pearlitic class. In America natural nickel-chromium steel is made from certain ores found at Mayari, Cuba. When converted into steel, a large part of the chromium is wasted, and when the highest quality is required the synthetic alloy steels are superior.

**Manufacture and Treatment of Nickel-Chromium Steel.** Nickel-chromium steel is manufactured in crucible, electric or open-hearth furnaces, but mostly in the latter. Care is needed in refining the steel in order to secure clean metal, also in teeming and handling the ingots. Analysis control is important, as it secures easier heat-treatment and constant machining properties. Billets must be carefully warmed and preheated before being placed in the forging furnace. Nickel-chromium steel is rather difficult to forge and roll. It will not weld, and is apt to develop laps and seams, unless due precautions are taken. The steel has a narrow range of forging temperature. Care must be taken that the steel is not burned ; it should not be forged above 1100° C. or below a yellow heat, and it must not be hammered with a cold centre. The dies used must be clean and not cold. In forging, billets of cross section suitable to the work should be chosen. For high-grade material, some makers machine off the surface of bars to ensure the removal of all surface defects.

In drop-forging nickel-chromium steels, the forging heat must be watched very carefully, and the operations must not be too severe. All forgings should be annealed carefully to overcome forging strains.

The heat-treatment of nickel-chromium steel is carried out on much the same lines as for simple nickel or chromium steels. The steel is hardened by quenching in oil or water from about 30° C. above the critical range, tempered by reheating to a temperature to suit the work on hand, and then quenched in water. Annealing for machining takes places at a temperature about 40° C. below the critical range.

Heat-treating for forging nickel-chromium steel consists in first carefully annealing the steel, then placing in a furnace at black heat and bringing it gradually and uniformly to a temperature somewhat above the critical range.

The antecedents in the heat-treatment of nickel-chromium steel affect its physical properties. If the steel has been overheated or not properly heated for forging, etc., it requires special treatment. The effect of size, i.e. cross section, has a marked influence. A 1-in. diameter section quenched in oil gives the same physical properties as a 2½-in. to 3-in. section quenched in water.

**Mechanical Properties of Nickel-Chromium Steels.** The simultaneous presence of nickel and chromium in steel raises the elastic limit combined with higher ductility and imparts greater hardening power, resilience and resistance to wear.

The static properties of the low-nickel chromium type (Fig. 31) are equal to those of the higher nickel grades, but the latter are somewhat superior dynamically.

Above a certain percentage of nickel and chromium (Ni + Cr + C over 5%) the steels become air-hardening. A typical composition is as follows—Carbon 0·25 to 0·35% ; chromium 1·1 to 1·5%, nickel 3·75 to 4·75% ; manganese 0·4 to 0·75%. These air-hardening nickel-chromium steels are used for parts requiring high strength. They show no mass effect, i.e. they harden throughout the mass, independently of the size of the section. Hardened from about 820° C. in air, they give a tensile strength of over 100 tons per sq. in. with 10 to 13% elongation. They can, however, be softened by tempering, and in this condition show a high impact value.

By slightly varying the nickel and chromium contents, keeping the carbon and manganese the same, a wide range of tensile strength can be obtained in the heat-treated condition. With 3 to 3½% nickel and 1·0 to 1·2% chromium, 75 to 100-ton steel is obtained, which shows a high impact test when

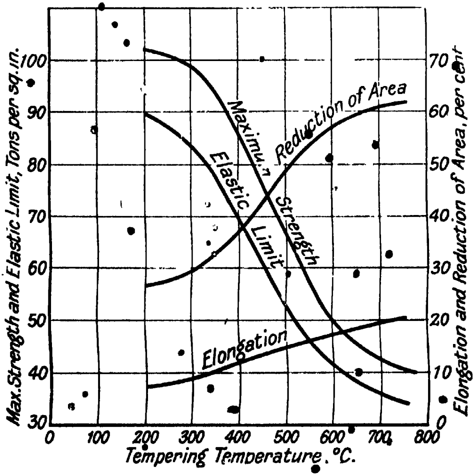

FIG. 31.—MECHANICAL PROPERTIES OF TYPICAL NICKEL CHROMIUM.
(0·35% C.; 1·0 to 1·5% Ni.; 0·5 to 0·75% Cr.)

tempered, but care must be taken not to temper too high or the steel starts to harden up again.

By slightly reducing the chromium, 60 to 75-ton steel or 50 to 60-ton steel (chromium 0·5%) may be produced, which shows an Izod test of about 70 ft.-lb. on tempering at 650° C. The fatigue range of nickel-chromium steel is roughly the same as the maximum strength ; thus, air-hardening (100-ton) steel showed a fatigue range of about ± 55 tons, and another steel showing a maximum strength of 57 tons per sq. in. had a fatigue range of ± 27·5 tons.

As an instance of the high quality of steel products of this type, there has recently been produced by the Hadfield Company a nickel-chromium steel possessing a tenacity of 108 tons per sq. in. with an elastic limit of 90 tons per sq. in., 15% elongation and 54% reduction of area. The ball hardness is 477 and the shock test of a notched Fremont test piece 5·3 kg.-m. (40 ft.-lb.), with 7° angle of bend.

In steel which is called upon to resist shocks, the impact test is the controlling factor. Having decided the elastic limit and ductility required, that steel is most desirable in which it is possible to develop the impact value to the highest degree. It is on account of their high dynamic strength that nickel-chromium steels are widely used in parts which have to resist shock and live loads. Nickel-chromium steels exhibit the phenomenon termed temper brittleness; in other words, when these steels are tempered in a range of 200° to 600° C. and cooled slowly from the tempering temperature, they give low notched bar or impact tests. If, however, the steels are cooled quickly from these temperatures (as, for example, by quenching in water) the impact value is not depreciated. A specimen containing 0·4% carbon, 3% nickel, and 0·8% chromium had its impact value reduced to one-fifth by cooling in the furnace instead of quenching in water. There is a critical range of about 450° to 550° C. in which the effect is most developed so that whatever the method of cooling the notched bar test is low. No difference in microstructure is apparent between the brittle condition and that showing a good impact test. Not all nickel-chromium steels are susceptible to temper brittleness. The condition appears more frequently in open-hearth than in electric steel. It may also be mentioned that temper brittleness has been observed in some chromium and molybdenum steels.

Nickel-chromium steel cannot be machined at extremely high speeds, so that the speed is generally reduced though the feed can be somewhat increased.

Nickel-chromium steel is used for case-hardened parts. As mentioned in Chapter III, all case-hardening steels are low in carbon their strength being obtained by an alloying element. By the use of nickel and chromium together, the strength of case-hardening steel may be more than doubled, as shown in Table XI.

## TABLE XI

MECHANICAL PROPERTIES OF CASE-HARDENING STEELS

| Type of Steel. | Quenched from, ° C. | Max. Strength, Tons per sq. in. | Izod Test, ft.-lb. |
|---|---|---|---|
| Ordinary Carbon . . | 925 | 32 | 40 |
| 2 % Nickel . . . . | 900 | 36 | 50 |
| 3 % " . . . . | 890 | 45 | 40 |
| 5 % " . . . . | 880 | 50 | 30 |
| 3½% Ni + ½% Cr . | 880 | 55 | 30 |
| 4 % Ni + 1¼% Cr . | 880 | 55 | 20 |

The case on nickel-chromium steel is harder than that on simple nickel steel, but simple carbon steel gives the hardest case of all.

Case-hardened nickel-chromium gears withstand shock and abrasion well; they should be tempered in oil to relieve strains after treatment to give the best core and case.

**Uses of Nickel-Chromium Steel.** The nickel-chromium steels described above, with low percentages of nickel and chromium have the advantages of being low in price and readily machined. All grades are used in automobile construction, the carbon varying from 0·22 to 0·55%. Nickel-chromium steel gears (not case-hardened) wear extremely well. The teeth burnish over and give better service than ordinary case-hardened gears.

Nickel-chromium steel is also used for parts of aeroplane engines, and for engineering parts of high strength. Large ingots of this steel are forged into shafts for marine purposes. The main girders of a railway bridge in Germany have been constructed of nickel-chromium steel. The weight is reported as 35% less than if mild steel had been employed. The structure has been in use nine years with entire satisfaction.

Nickel-chromium steel is employed in the manufacture of armour plate, the impact face of which is hardened by a carbonizing process. Nickel imparts the property of not cracking when perforated by a projectile, and chromium combines hardness with high elastic limit and high resistance to shock. Armour from 6 in. to 15 in. thick has the following analysis—Carbon 0·33%; nickel 3·5 to 4%; chromium 1·5 to 2%; the mechanical properties of the body of the plates being—Ultimate strength 45 tons per sq. in.; elongation 24%; reduction of area 60%. Medium armour, i.e. below 6 in. thick and not face-hardened, is given high properties throughout by proper heat treatment. It is used for protective decks and barriers to protect from secondary battery fire. This steel has a composition somewhat as follows— Carbon 0·30% ; nickel 3·65% ; chromium 1·45%. A steel like the latter but with higher carbon has also been used by the French for armour-piercing projectiles. Some firms have added 0·25% of tungsten or molybdenum to the composition.

The quality and strength of nickel-chromium steel has been developed at the Hadfield Works in a remarkable degree, as exemplified in the wonderful performance of the armour piercing projectiles up to 18 in. calibre, manufactured by Messrs. Hadfields. These are capable of penetrating the thickest armour afloat, a test which is probably the most severe to which steel can be subjected. In the continuous contest between armour and projectile, the victory has rested now with one side, now with the other. It may be said that at least for a period modern hard faced armour was capable of resisting the penetration of projectiles under the practical conditions of long range engagements. This is past unless some further development of armour is brought about. To-day the projectiles developed by the Hadfield Company are capable of passing undamaged through the strongest naval defences, including the very severe test of impacts at considerable angles of obliquity. During the war the capacity of output of large armour piercing projectiles (12 in. calibre and upwards) at the Hadfield Works was nearly one thousand per week, so that there was never any danger of the British Fleet running short of ammunition of this type.

Fig. 32 shows three Hadfield 15 in. calibre projectiles which have actually perforated thick hard-faced armour of the latest type and been recovered practically undamaged after completing this difficult task.

It is interesting to note that although armour-piercing projectiles are essentially perforating tools, nickel is always employed in their composition,

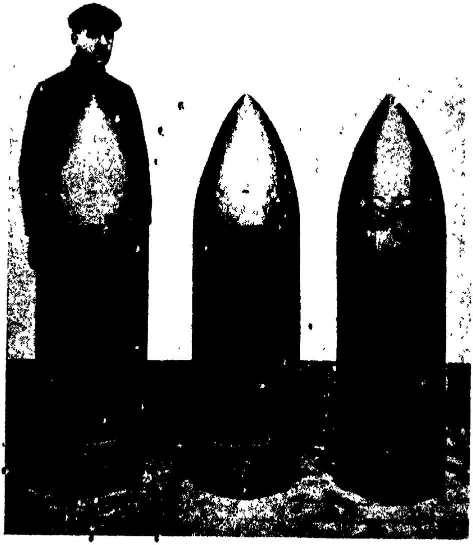

FIG. 32.—GROUP OF HADFIELD 15-IN. PROJECTILES AFTER PENETRATING HARD-FACED ARMOUR 15-IN. THICK.

whereas it is not used, in fact is detrimental, in tool steel.

Steels with high percentages of nickel and chromium have recently been developed on the

Continent on account of their rust-resisting properties. Particulars of two of the alloys are given in Table XII.

TABLE XII

NICKEL-CHROMIUM RUST-RESISTING STEELS

| | | |
|---|---|---|
| Analysis—Carbon, % . . . . | 0·1–0·3 | 0·1–0·3 |
| ,, —Nickel, % . . . | 1–3 | 6–9 |
| ,, —Chromium, % . . | 10–15 | 20–23 |
| Structure . . . . . . . | Martensitic | Austenitic |
| Elastic limit, tons/sq. in. . . | 39 | 26 |
| Max. strength, tons/sq. in. . | 51 | 49 |
| Elongation, % . . . . . | 15 | 50 |

The martensitic alloy is self-hardening but, by heating to 680°–750° C. and cooling slowly, it can be made workable. The austenitic alloy is treated by heating to 1100°–1200° C. and cooling quickly. It is non-magnetic. The alloys are resistant to the corrosive action of the atmosphere, sea water, cold 10%-nitric acid, boiling 50%-nitric acid, alternate wet and dry tests, and of hot gases. The austenitic alloy, which is the more resistant of the two, has been employed for valve spindles. The martensitic alloy has been used for turbine blades.

# CHAPTER X

## CHROMIUM-VANADIUM STEEL

VANADIUM requires the presence of another element in steel to bring out its intensifying action to the fullest extent. A combination generally used for this purpose is chromium-vanadium steel. The addition of vanadium to steel is considered in Chapter VIII, and the hot working of chromium-vanadium steel presents no special difficulties. Vanadium forms complex carbides with chromium which greatly strengthen the steel, and also has a beneficial effect on the properties of the steel in the quenched and tempered condition.

### Mechanical Properties of Chromium-Vanadium Steel

The physical properties of chromium-vanadium steel are like those of nickel-chromium steels except that the reduction of area is slightly greater (Fig. 33). It is more easily machinable than nickel-chromium steel, and is generally free from surface defects.

A typical chromium-vanadium steel contains—Carbon 0·3 to 0·4%; chromium 1·0 to 1·5%; vanadium 0·15 to 0·25%. Mechanical properties of steels with high and low carbon content are shown in Table XIII.

Chromium-vanadium steels offer resistance to diminution in tensile strength and elastic limit on tempering up to 450° C. or more. They may be treated to give a tensile strength of 100 tons per sq. in., combined with 8% elongation and 15 to 18% reduction of area—a useful set of properties needed to meet some of the requirements of modern engineering practice.

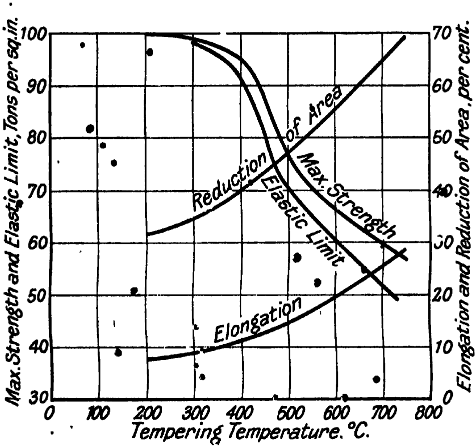

FIG. 33.—MECHANICAL PROPERTIES OF CHROMIUM-VANADIUM STEEL.

(0·30% C.; 1% Cr.; 0·20% V.; oil-hardened.)

## TABLE XIII

MECHANICAL PROPERTIES OF CHROMIUM-VANADIUM STEELS

| | | |
|---|---|---|
| Carbon content, % . . . . | 0·4 | 0·25 |
| Steel quenched at, . . . | 870° C., oil | 850° C., water |
| Tempered at . . . . . | 650° C. | 650° C. |
| Elastic limit, tons/sq. in. . | 45 | 50 |
| Max. strength, tons/sq. in. . | 62 | 54 |
| Elongation, % . . . . . | 20 | 24 |
| Reduction of area, % . . | 57 | 70 |
| Fatigue range, tons/sq. in. . | ± 30 | — |
| Izod test, ft.-lb. . . . . | 85* | — |

* Increases rapidly with tempering temperature, and may be 115 ft.-lb. or more if the steel be tempered at 750° C.

The fatigue range of another chromium-vanadium steel having a tensile strength of 63 tons was ± 33 tons, so that it may be considered approximately equal to the maximum strength.

Various experts have carefully studied the claims made that "steels containing vanadium as a constituent are stronger than those free from that element, that they are sounder and more homogeneous and that they have a higher fatigue strength." As regards fatigue strength, the claim has been tested directly and was not found to be substantiated. Moreover, any increase in strength resulting from the addition of vanadium is not commensurate with the cost of the element. Dr. Aitchison has pointed out that tests made on a pair of chromium steel forgings with and without vanadium were found to give practically the same results, though the steel used in the former, owing to the addition of vanadium, was naturally much more expensive.

**Uses of Chromium-Vanadium Steel.** Chromium-vanadium steel is used for driving axles and other forgings for locomotives, and for automobile springs and axles which are found to withstand repeated alterations of stress in the neighbourhood of the elastic limit without taking a permanent set. The steel has also been applied to the manufacture of torpedo tubes, compressed air flasks, gun forgings, and the like.

# CHAPTER XI

## HIGH-SPEED TOOL-STEEL*

**Developments.** The rapid development of cutting-steels in the last fifty years, as compared with the preceding centuries, lies in the fact that the manufacturing industries of the civilized world demanded a means of securing largely increased production without a commensurate increase in cost. This was obtained by speeding up the individual machines, and for this purpose the tool steel must meet the following requirements:—

(1) The tool must be harder than the material cut and resistant to wear and severe service.

(2) It must not soften when subjected to the heat developed by friction.

Ordinary carbon tool-steel contains as an average 1% of carbon, present as iron carbide ($Fe_3C$) held in solid solution due to the rapid cooling of the steel. It is, however, in a metastable condition and softening commences at a temperature of about 200° C. (corresponding to light cut and feed at slow speed). On the other hand, high-speed steel shows only a small decrease in hardness when raised to a dull red heat, and retains its cutting edge at temperatures which would at once destroy the cutting ability of simple tool-steel. It has produced a revolution in machine shop work throughout the world.

The development of high-speed steel, as shown in Table XIV, started about 1868 when Robert

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* The treatment of the historical development of tool steel adopted in this chapter closely follows the lines laid down in Mr. D. M. Giltinan's paper in the *Transactions of the American Society for Steel Treating*, September, 1921, p. 716.

## TABLE XIV

### THE DEVELOPMENT OF HIGH-SPEED STEEL

| Year. | Composition per cent. | | | | | | | | Cutting Speed.* |
|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | Si | Cr | W | Va | Co | Mo | Feet per min. |
| (Carbon tool-steel) | 1·00 | 0·20 | 0·20 | 0·20 | — | — | — | — | 16 |
| 1868 (Mushet) | 2·30 | 2·57 | 1·15 | 1·15 | 6·62 | — | — | — | — |
| 1868–1870 | 2·00 | 1·70 | 0·90 | 0·40 | 5·5 | — | — | — | 26 |
| 1890–1892 | 1·40 | 0·27 | 0·20 | 1·70 | 8·0 | — | — | — | — |
| 1900 | 1·60 | 0·30 | 0·15 | 3·80 | 8·0 | — | — | — | 60 |
| 1902 | 1·50 | 0·20 | 0·25 | 2·50 | 10·0 | — | — | — | — |
| 1903 | 0·70 | 0·25 | 0·15 | 3·00 | 13·0 | — | — | — | 80 |
| 1904 | 0·70 | 0·20 | 0·10 | 3·00 | 18·0 | — | — | — | — |
| 1904 (Mushet) | 0·60 | 0·12 | 0·05 | 3·44 | 17·25 | — | — | — | — |
| 1905 | 0·70 | 0·20 | 0·20 | 7·00 | 24·0 | — | — | — | — |
| 1906 | 0·67 | 0·10 | 0·04 | 5·50 | 19·3 | — | — | — | 100 |
| 1906 | 0·65 | 0·13 | 0·08 | 6·00 | 10·0 | — | — | 0·8 | — |
| 1906 | 0·70 | 0·05 | 0·05 | 6·00 | 18·0 | 0·50 | — | — | — |
| 1908 | 0·65 | 0·20 | 0·20 | 4·00 | 18·0 | 1·00 | — | — | — |
| 1910 | 0·62 | 0·15 | 0·15 | 4·00 | 14·0 | 1·00 | — | — | 180 |
| 1913 | 0·68 | 0·20 | 0·20 | 4·00 | 14·0 | 2·00 | — | — | 240 |
| 1914 | 0·70 | 0·20 | 0·20 | 3·50 | 18·0 | 1·50 | 4·50 | — | Up to 500 depending on the feed and cut and the quality of the material |
| 1915 | 0·65 | 0·25 | 0·15 | 3·50 | 14·0 | 1·30 | 4·50 | — | |
| 1916 | 0·75 | 0·28 | 0·10 | 4·40 | 16·5 | 0·70 | 5·00 | 0·3 | |
| 1917 (German) | 0·85 | 0·28 | 0·07 | 5·00 | 18·0 | 1·20 | 5·00 | — | |
| 1922 (typical) | 0·62 | 0·10 | 0·18 | 3·75 | 16·5 | 1·0 | | | |

* The number of variables in metal-cutting is very large; the cutting speeds stated must be taken only as representative figures. *See also Metal Cutting Tools and Speeds*, by W. G. Burley (Pitman, 2s. 6d. net. *in preparation*).

Mushet, of Sheffield, discovered the value of manganese in the manufacture of Bessemer steel. In experimenting on the value of manganese on tool-steel he found that one composition of manganese hardened when cooled in air. Analysis showed that a considerable proportion of tungsten was present in addition. This steel was given the trade name "air-hardening steel." It was soon afterwards found that cooling from 1000° to 1100° C. in an air blast gave better results for tools. An important step in the further improvement of this steel was taken by the late Mr. Maunsel White, head of the chemical and testing laboratories of the Bethlehem Steel Company, who found that a great increase in cutting powers resulted from heating such special steel tools to a very high temperature, between 1200° C. and 1400° C., when about to harden them. Like others, in his various experiments he had noticed the great difficulties in the manufacture and dressing of Mushet tool steel. These experiments also led to the discovery that, by replacing the manganese by chromium, greatly reducing the carbon, and increasing the tungsten contents, superior tool steel was obtained which could readily be forged to shape. Mr. Frederick Taylor was originally Chief Engineer of the Midvale Company, and when he joined the Bethlehem Company he became associated with the eminent American metallurgist Mr. Maunsel White. It was Mr. Taylor who also gave great attention to machine shop methods, resulting in a great increase in their efficiency.

Modern high-speed steel may be said to have been introduced at the Paris Exposition in 1900. The tools there shown did not lose their temper or toughness at red heat, the temperature of the chips formed being about 300° C. Further work showed the advantage of higher chromium and tungsten and placed the carbon content between 0·6 and 0·8%. It was found that the maximum efficiency was obtained with a chromium content of 3 to 4% and about 18% of tungsten. Molybdenum was also tried in the place of tungsten, and was found to yield a very good high-speed steel which did not require as high a hardening temperature, 1% of molybdenum being about equivalent in effect to 2% of tungsten. It has not, however, replaced tungsten for this purpose, as in some cases it was found rather uncertain, and to deteriorate after repeated heating for dressing and treatment. As now used, molybdenum is more an auxiliary than a major constituent. About 1906 to 1908, vanadium was added to high-speed tool-steel, and although expensive it was found that the increase in cutting efficiency compensated for the additional cost. Its action in increasing the durability or life of the tool when working at high temperatures has not been explained fully. With a content of 2% vanadium it was found possible to decrease the tungsten content somewhat. In later years, cobalt has been added to high-speed steel with some success, but it has not come into general use. 5% of cobalt is claimed to impart greater durability and more uniform performance. It may have an advantage for certain heavy roughing-cuts and for machining hard nickel-chromium steel in the lathe owing to its ability to hold an edge. It must be remembered that chemical analysis alone does not yield a good high-speed steel. Unless the raw material is physically sound, the melting carried out skilfully, and the steel forged with care and heat-treated correctly, the highest performance of the tools will not be obtained. The steel must be free from seams, internal cracks and fibre, and both the longitudinal and transverse fracture should show a smooth uniform structure.

**Manufacture of High-Speed Steels.** The manufacture of high-speed steels involves no different processes from those by which high-grade cutting-steels have been made for many years past, although refinements and improvements are made from time to time. The steels are mostly made in the crucible, although the electric furnace is gaining ground due to its ability to refine low-grade material and to re-melt tool-steel scrap rapidly in fair quantities. In the crucible process, definite amounts of high-speed steel scrap, low-carbon bar iron, ferro-chromium, ferro-vanadium and tungsten powder or ferro-tungsten are packed in crucibles and sealed, the tungsten being on top on account of its greater density. Each pot contains about 100 lb. of steel, and a number are put into a furnace at one time, melted, and mixed by pouring into a ladle preparatory to casting. Sometimes the pots are teemed directly into a mould by hand-pouring (*see* cover illustration on this book). Owing to a tendency to pipe, the top of the ingot mould may be kept hot. When the metal has solidified, the moulds are stripped and the ingots cooled very slowly, e.g. in ashes. High-speed steel shows a coarse grain and dark colour and as a rule, strong columnar structure, with the crystal axes normal to the cooling surface. This structure is not so pronounced if the casting temperature is low, and it is subsequently destroyed by heating and working. The ingots are annealed to remove casting strains and then heated for rolling or hammering into bars which are re-annealed for machining.

For forging, the steel is heated very slowly to a temperature of 1000° to 1100° C., and work is discontinued when the steel begins to stiffen under the hammer. About 88% reduction should be made in ingots about 8 in. square. The forging eliminates ingot structure and breaks up and disseminates the carbides uniformly.

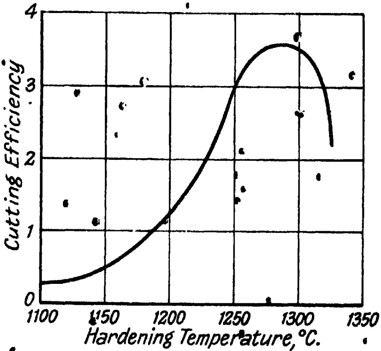

FIG. 34.—ILLUSTRATING THE INFLUENCE OF HARDENING TEMPERATURE ON CUTTING EFFICIENCY OF HIGH-SPEED STEEL.

Microscopic examination shows that annealed high-speed steel consists of a matrix of solid solution of iron and tungsten with globules of carbides or tungstides of iron and chromium or a combination of both. Quenching from ordinary temperatures (800°-950° C.) produces no appreciable change in structure. On heating to 1250°-1300° C., however, the carbides are brought into solution, the steel becoming finely martensitic in structure, and the full cutting powers are developed (Fig. 34). Chromium and tungsten are known to lower the carbon content of pearlite, thus accounting for an excess of free carbides in high-speed steel, and together with manganese they prevent the separation of cementite. The transformation range is lowered below room temperature so that an austenitic structure results in spite of relatively slow cooling.

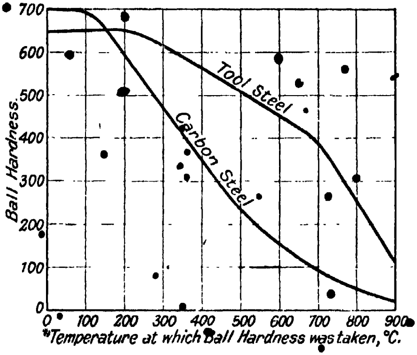

FIG. 35.—COMPARISON BETWEEN RED-HARDNESS OF CARBON STEEL AND OF HIGH-SPEED TOOL STEEL.

The property of red-hardness exhibited by high-speed steels may be defined as resistance to softening by tempering (Fig. 35). It increases slightly with the quenching temperature. Red-hardness is due to the conversion of the austenitic structure to martensitic on heating. It may be supposed that the carbides not only go into solution very sluggishly on heating but separate sluggishly on reheating, so that the tool is able to run for a long time at red-heat.

The degree of secondary hardening is a function of the carbon and chromium content, and probably to a lesser degree of the other alloying elements. The temperature range in which secondary hardening may be obtained is a comparatively wide one—about 100° C.

**Heat-Treatment of High-Speed Steel.** The heat-treatment of high-speed steel is a most important branch of the cutting tool industry for the good qualities which a tool might have possessed can be destroyed to a greater or less degree by faulty heat-treatment.

When high-speed steel is cooled from 930° C. there is a halt or rest point at about 700° C. to 750° C., but on cooling from 1250° C. there is no arrest point. Above 1200° C., the chromium and tungsten have a greater affinity for carbon than iron has, and a double carbide of these metals is formed which persists on slow cooling.

Taylor and White cooled the tools quickly to below 850° C., and used a lead bath at 565°–620° C. for a tempering or low temperature treatment.

The procedure in heat-treating tool-steel usually adopted at the present time is as follows—

The steel is preheated slowly up to 820°–900° C. and uniformity of heating is obtained by protecting thin sections. Atmospheric oxidation is avoided as far as possible. The steel is then brought up to the high quenching temperature as quickly as possible, the atmosphere in the furnace being controlled carefully to avoid oxidizing conditions. The best hardening temperature is 1300°–1320° C.

The steel is then quenched in a bath of molten salts or oil. Cooling in a dry air blast is not so common now, as oxygen from the air may form a scale of oxide. A suitable salt bath for the quenching operation consists of a mixture of calcium chloride, sodium chloride and potassium ferro-cyanide in proportions depending on the required temperature. If an oil bath is used, linseed oil or cotton seed oil are suitable. The latter part of the cooling on quenching may be slow when tempering is not required, but the hardened tool is usually tempered to remove quenching strains and bring out the red-hardness to the full. An oil bath may be used for this purpose. Milling cutters and similar tools are drawn to a degree depending on the material they are intended to cut. The highest secondary hardness (Brinell ball hardness of 610) is developed by heating to between 550 and 600° C. It has been suggested that sharp changes in magnetic properties constitute a test which may be valuable for determining whether a tool has been correctly tempered. When high-speed steel is heated above 650° C., a transformation to the pearlitic condition ensues. The steel can be annealed or softened by heating to about 800° C. and cooling in the furnace or in lime or ashes. The grain may be refined by heating to 950° C. and cooling in air.

**Testing Tool-Steels.** Some tool-steels will and some will not scratch glass, but the hardness when cold (ball and scleroscope numbers, also file tests) does not seem to be the determining factor of usefulness, and has no connection with machine shop practice.

No test of high-speed steel seems to take the place of a trial at actual work. It has been found that greater durability of tools is obtained by determining the critical speed, and the durability depends on the material being cut. The maximum durability of high-speed steel occurs at higher speed than for carbon tool-steel. Herbert announced that certain high-speed tools have two critical speeds being less durable above, below, and between these speeds (Fig. 36). This may account for some anomalies that have appeared in tests.

If, in addition to higher speeds, heavier cuts are required, tools are generally re-designed to provide the greater strength necessary.

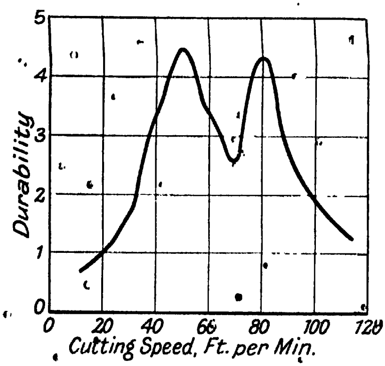

FIG. 36.—ILLUSTRATING TWO CRITICAL CUTTING SPEEDS OF HIGH-SPEED STEEL.

**Applications of High-Speed Steel.** The practical results of high-speed steel are apparent in the manufacturing establishments of to-day. In addition to the saving power per unit of metal cut off, there is a reduction in the cost of plant for given output, and in the general and overhead charges.

High-speed steel is also used for exhaust valves in internal combustion engines and for dies for extruding hot metals.

**Possible Substitutes for Tungsten High-Speed Steel.** Owing to the scarcity of tungsten during the war, substitutes for tungsten high-speed steel were brought out, for some of which rather extravagant claims were made, but these substitutes have not met with much application.

An alloy not included in the above, which can be used at high cutting-speeds, may be mentioned. The material, Stellite, invented by Elwood Haynes, is hard and fine-grained, and may be heated to a bright red or orange without softening. Its approximate constitution is as follows: Cobalt 60%; Molybdenum 22%; chromium 11%; iron 3%; manganese 2%.

The users of high-speed steel are, as a rule, conservative, and some rely solely on analysis. Because a certain composition has proved itself good, however, it would be a mistake to refuse to try any new steel or alloy which may possess merit. In the high-speed steel of to-day, carbon is the hardener, the double carbide of tungsten and chromium conferring the cutting edge. It is possible that cutting tools will be developed, however, which are independent of carbon, and which are not appreciably softened at reasonably high temperatures. The realm of alloys is immense, and we may say that only the fringe has been investigated. The possible combinations of the metals are almost infinite in number, and it does not appear too much to expect that one or more alloys may be discovered which possess the hardness and toughness of steel combined with resistance to deterioration of cutting properties at high temperatures.

# CHAPTER XII

## THE TREND OF PROGRESS

**Recent Developments.** The Great War stimulated intense activity in metallurgical production but probably no branch made greater progress than the making and heat treating of special steels. The progress chiefly consisted in improvements of existing processes and in detailed and systematic heat treatment of steels very sensitive to heat. The new and exacting applications which arose, e.g. in aircraft, necessitated the production of steel possessing special properties and of extreme reliability, but it cannot be said, nor would it be expected in such times of stress, that any fundamentally new steel was discovered. Probably the chief feature in this direction lay in the production of alloy steels which retain their strength at high temperatures—850° C. and above—and also offer resistance to oxidation, erosive action, shock and abrasion. As examples of applications in which such properties are required, the following may be mentioned—exhaust valves for internal combustion engines, turbine blades, and apparatus in which chemical operations are carried out at high temperatures. The most promising steels are those containing 12 to 13% of tungsten or chromium (the carbon being high) but high nickel chromium alloys have been developed for the same purpose. The increase in the number of electric furnaces during the war has been mentioned, and there seems little doubt that where the highest quality is demanded, the electric furnace will be the principal source of alloy steels of the future for some time to come.

**Importance of Research.** The advance of civilization depends on the work of the metallurgist, and the contributions of this country to the science of metallurgy have been of first-class importance. Professor Sauveur, of Harvard University, has put it on record that "if the contributions of English metallurgists and chemists were withdrawn, the entire structure of the iron and steel industries would collapse." It is fervently to be hoped that we keep in the van of metallurgical discovery, and to this end intensive research on broad lines is necessary.

Pure science should not be neglected because it produces no immediate practical results. The pure science of to-day is the applied science of to-morrow. The sole difference between pure and applied science is one of degree and not of fact, and from one fundamentally new conception or view point a great number of applications may arise.

The result of a fundamental discovery may be likened in effect to the action of a stone thrown into the middle of a pond, the disturbance of which passes outwards in ever widening ripples, its influence reaching larger and still larger zones.

In the realm of ferrous metallurgy, no better illustration of the truth of the above can be obtained than that of the discovery of manganese steel, in 1882, by Sir Robert Hadfield. Not only was this material a curious alloy with subversive but extremely useful properties, but its discovery revolutionized the whole trend of metallurgical thought. This careful and persistent research, resulting in the discovery of manganese steel, largely laid the foundation of the modern knowledge of special steels. In its further consequent effect the influence of this invention has also helped to revolutionize certain branches of engineering.

Research is also the bed rock of efficiency. It leads to the elimination of waste and to the conservation and better utilization of steel.

The discovery of new products and processes involves problems of the greatest intricacy, in the solution of which a multitude of methods are employed each seeking to reveal some new information. In the following pages there is given a brief indication of some of the more obvious directions in which research is possible and where new knowledge may be obtained.

**Testing of Materials.** One of the most important strength characteristics of a material, from the point of view of the designer of structures or machines, is the fatigue range. Much work still remains to be done in explaining the real meaning of fatigue and shock tests, and in determining and standardizing the most suitable type of apparatus for effecting such tests. Recent work has tended to indicate that the fatigue strength of steel is a function—nearly one-half—of the maximum tensile strength, but Professor F. Jenkins' experiments have thrown much light on the phenomenon of fatigue and the part played therein by the elastic limit. Work has been done in America, by Professor Moore and others, which suggests that the fatigue strength of steel can be obtained more rapidly than with the usual methods, by observing the increase in temperature of the specimen under stress reversal. This development may provide a more rapid means of carrying out fatigue tests, which if found correct would be of considerable advantage.

In addition to an improvement in the more reliable methods of mechanical testing, it is probable that different forms of non-destructive tests of finished parts will be developed. These tests will indicate the condition of the parts without destroying them, and without assuming that the material is precisely the same as indicated by tests made on specimens from other portions of the material,

In this connection a good deal has been done to develop methods of magnetic analysis. Satisfactory results have been obtained in testing the homogeneity of rails and other articles, but success in general, as opposed to particular, cases has not yet been reached. It may be mentioned that the coercivity is considered the best criterion for testing mechanical hardness. Electrical and magnetic tests of welds show considerable promise, at least as applied to butt welded plates and without doubt a really poor weld can be demonstrated.

Another non-destructive test is the measurement of electrical conductivity. This property has been shown to vary with the molecular constitution of steel, but a good deal of further work seems necessary before conductivity results can be interpreted in terms of other properties.

**Examination by X-Rays.** Of recent years X-rays have been applied to the examination of steel and have proved useful in the detection of blowholes and internal faults.* The method is limited by the thickness of steel which can be penetrated by the rays, and by not being sensitive to the detection of cracks, hair lines, etc., but with improvements in apparatus and technique further development in this direction may be anticipated. X-ray photographs do not, however, give any information as to the nature of aggregation of constituents.

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* See also *Industrial Applications of X-Rays*, by P. H. S. Kempton, uniform with this volume. (Pitman, 2s. 6d. net.)

A further application of X-ray examination lies in the adaptation of the methods of Hull and Bragg to the determination of the crystalline structure of iron in its allotropic modifications. It has been shown by Dr. Westgren that $\alpha$-iron has a cube centred lattice, and $\gamma$-iron a face centred cubic lattice, while the so-called $\beta$-iron is the same as $\alpha$-iron. Further work may be expected to throw light on the constitution and fundamental properties of alloy steels.

In a recent investigation (1920) by Maurer into the authenticity of the so-called hard adamantine form of iron formerly described as $\beta$-iron, new experimental results are given which show that no such form exists and that its effect with regard to the hardening process of steel must be excluded. This was confirmed many years ago by the facts noted relative to Hadfield manganese steel. In saying this, it must still be admitted that none of the new theories of the hardening of steel are completely satisfactory.

**Investigation and Control of Manufacture and Treatment.** The microscope is a valuable research instrument to the metallurgist. In this connection further information on the constitution and behaviour of alloy steels may be expected from a more thorough investigation of grain size, the examination of constituents at higher magnifications and investigations into the applicability of the ultra-microscope.

Pyrometric control within narrow limits is essential in heat treating alloy steels. There appears to be scope for an extended use of high range instruments in measuring and controlling the temperature in furnaces, casting temperatures, etc.* Progress is also being made in the use of fool-proof automatic temperature control to a predetermined programme.

Another direction in which improvements in steel may be expected lies in a thorough investigation of the effect of dissolved or occluded gases. There is good reason to believe that the effects exerted by gases are deleterious in most cases. It is important to ascertain not only the amount of the occluded gases but the forms in which they are present. The improvement in the magnetic quality of silicon steels obtained by Dr. Yensen by melting in vacuo has been mentioned in Chapter V, and it appears probable that means will be found for producing on a larger scale steels free from occluded gases, which will show highly important properties. This is probably an important subject of research for our younger metallurgists.

**Colloidal Chemistry in Metallurgy.** It is well known that the properties and qualities of steel are greatly influenced by the magnitude of its particles which may vary from macroscopic size down to molecular magnitudes. The application of the principles of colloid chemistry throws an important light on the constitution of steel and the formation of different structures, and may lead to a more thorough understanding and control of its properties. The structural components induced by different rates of cooling carbon steel give the well-known series—Austenite—Martensite — Troostite — Sorbite — Pearlite — which may be considered a dispersoid system. When a steel has been quenched and no precipitation takes place, the size of the particles in solution is the same as that at the higher temperature. 1 $\mu\mu$ or less. Austenite represents the most highly dispersed, or molecular phase formed on quick cooling. As collection of these probably colloidal particles takes place to a critical dispersion, a martensitic structure is formed. On heating, the accumulation of these small particles takes place into masses of a size visible under the microscope. Pearlite represents the most grossly dispersed size or a coagulated condition of ferrite-cementite solution. The intermediate members of the series are colloid solid solutions. It will be seen that if the growing of the disperse phase in steel can be prevented by a suitable protective colloid, a revolution in steel technique will be brought about. In this connection it may be mentioned that flaky and woody structure in nickel steel are obviated by small amounts of alloying elements which flocculate the trouble-making impurities.

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* See also *Pyrometers and Pyrometry,* by Ezer Griffiths, uniform with this volume. (Pitman, 2s. 6d. net.)

The addition of silicon, titanium or aluminium in small quantities to molten steel, with a view to producing sound metal by preventing the evolution of gas at the moment of solidification, is on a par with the protective action of certain colloids.

Another interesting application of the principles of colloid chemistry to the problems of ferrous metallurgy, is the theory of Dr. Newton Friend in connection with the complex and difficult subject of corrosion. This, too, was suggested some time ago by Dr. A. S. Cushman. Put briefly, the colloid theory of corrosion is as follows—On coming into contact with air and liquid water, iron slightly oxidizes to ferrous hydroxide which is produced in the colloidal condition, and this oxidizes in excess of air to a higher hydroxide, still in colloidal form. This higher colloidal hydroxide now acts catalytically, accelerating the oxidation of iron and itself undergoing a reduction to a lower colloidal hydroxide, only to be oxidized again as oxygen from the air diffuses towards it. When the colloid flocculates, rust is produced. The above theory is found to offer a satisfactory explanation for many phenomena which cannot be explained by the old theories; it also suggests new lines of attacking the protection of iron and steel from oxidation.

**Spectroscopic Analysis.** A reference may be made to the fact that the spectroscope has met with a few applications in the steel industry. One of these is the spectroscopic determination of constituents of steel. At present the method is only qualitative, but it forms a ready means of determining whether certain elements are present, and it is particularly useful in the case of rare elements; it also forms a check as to whether elusive elements which have been added to the steel bath have been completely eliminated during the course of the furnace operation. If it is merely required to determine whether certain elements are present, this method is in some cases more rapid than chemical analysis.

Another application is to the investigation of conditions in the course of a blow in the converter. From a spectroscopic examination of the converter flame it is possible to determine to what degree the oxidation and elimination of various elements by the blast has proceeded. This enables the operator to judge the correct stage at which to make the various additions, or to stop the blow at a predetermined composition of the charge.

**Investigation by Cinematograph.** In recent years the cinematograph has been applied to the investigation of problems involved in the determination of the strength of steel. As an example, the mechanism of breakdown on tensile and other test pieces has been studied and films have been prepared showing the course of these phenomena, and providing data additional to those observed by the naked eye. A further development of this work which may prove of considerable use, is the application of the ultra-rapid cinematograph camera, which has been constructed to take photographs at the rate of ten thousand per second, and even this speed is not the limit of the new method. It is probable that this means of investigation may throw considerable light on the mechanism of fracture of steel under shock or very rapid blows. The research made possible by this high speed apparatus, may bring out new facts in connection with these little understood problems.

**New Applications.** Many new applications of known alloy steels are to be expected, for example in structural work, rails, locomotives, boilers, etc., and in the mining industry, where great strength and resistance to erosion are necessary. As regards

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NOTE to Fig. 37

Mechanical tests on two test bars cut from the webs—

| | No. 1 Bar. | No. 2 Bar. |
|---|---|---|
| Yield point, tons per sq. in. . . . | 22·2 | 22·2 |
| Tensile strength, tons per sq. in. . . | 36·1 | 36·1 |
| Elongation, per cent. . . . . | 35·5 | 35·5 |
| Reduction of area, per cent . . . | 62·2 | 60·7 |
| Bending, 1½ in. bar over ¾ in. radius . . | 180° | 180° |

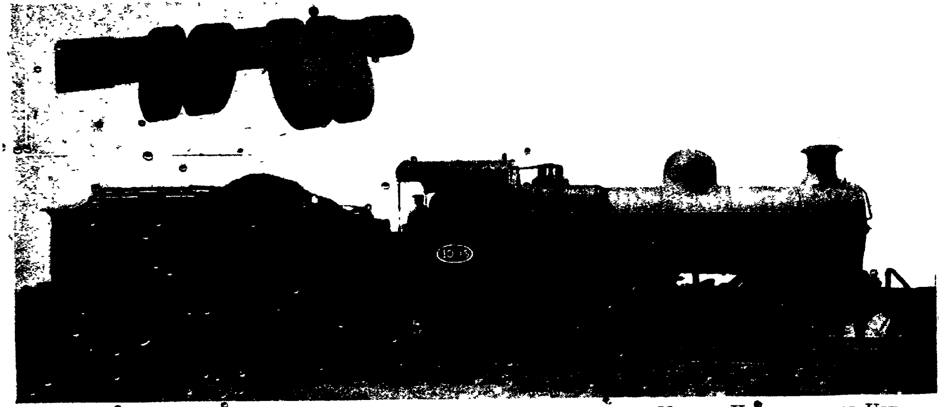

FIG. 37.—CRANK AXLE OF SPECIALLY HEAT-TREATED STEEL MADE BY MESSRS. HADFIELDS FOR USE ON THE GREAT CENTRAL RAILWAY LOCOMOTIVE ILLUSTRATED.

(See page 152 for Mechanical Tests for this Fig.)

locomotives in particular the use of alloy steels has been suggested for reciprocating parts, cranks, axles, etc., with a view to reducing weight without sacrificing strength. A locomotive crank axle of Hadfield's specially heat-treated steel which has been fitted on a Great Central Railway locomotive is shown in Fig. 37, particulars being given of the mechanical properties of the steel used on page 152.

The use of alloy steels is also finding increasing application in marine engineering, and the use of special steels is to be anticipated in power and transmission parts, as well as in those required to resist rust, and, when necessary, high temperature.

**New Steels.** The thirty years immediately before the war were prolific in the discovery of alloy steels, and it is difficult to imagine that there will be as great or numerous discoveries in an equal period dating from the present time.

From time to time the invention of a "super" steel is announced, the properties of which are due to the addition of "rare" elements. Unfortunately, these properties are hardly ever established or confirmed, and it appears probable that—apart from a fortuitous discovery—the invention of a "super" steel will only arise after much study and investigation, and an understanding of the real merits of steel made by the various processes.

The examination of the properties of iron alloyed with other elements is, however, being continued with increasing vigour, and valuable results—from both the immediate practical and the scientific points of view—are accruing to the world from the labours of the metallurgist. The practical manufacture and application of special steels presents problems of so many variables that it is hardly likely that they can ever be solved with mathematical exactness, and from a purely scientific point of view our knowledge of alloy steels is far from complete. New steels are certainly not exhausted, and trials are continually being made of alloys of promise. It is to be anticipated, however, that they will have to withstand severe criticism and tests before earning a place among the recognized steels.

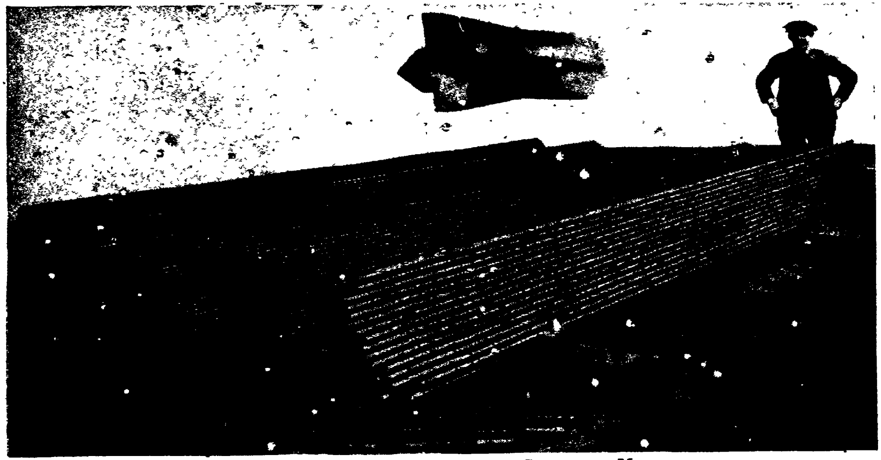

Fig. 38.—"Hecla" Hollow Drill Steel for Mines.
Made by Hadfields, Ltd., Sheffield.

# APPENDIX

## CARBON STEEL

SINGULAR as it may seem, notwithstanding the important part played by all the newer alloys of iron, carbon still maintains its premier position in determining the practical value of nearly all the various ferrous products. In other words there are few iron alloys in which, apart from the effect produced by the special element added, the presence of carbon is unnecessary. Whilst new alloy steels are often presented which are said to owe their advantages to one or more special constituents, it is quite overlooked that the improved qualities are frequently intimately connected with the carbon present. In fact, it may be said that most of these alloy steels depend for their properties on the particular combinations of the carbon present, with iron and other special elements.

For these reasons, and to afford a basis of comparison with the various special steels, the following notes on carbon steel are included.

A most important paper, entitled "The Influence of Carbon on Iron," was presented to the Institution of Civil Engineers in 1895 by Prof. J. O. Arnold, F.R.S., who made a valuable series of alloys of iron with carbon from an iron base of very pure Swedish "Lancashire" iron. The series comprised eight specimens ranging from 0·08 to 1·47% carbon content. The sum of the silicon, sulphur, phosphorus, and manganese contents did not amount to more than

## TABLE XV

### ANALYSES OF SPECIMENS OF CARBON STEEL INVESTIGATED BY ARNOLD

| Steel No. | Total Carbon. | Graphite in annealed Sample. | Silicon. | Manganese. | Phosphorus. | Sulphur. | Aluminium. | Iron ($H$ and $N$) by Difference. | Total Impurities. |
|---|---|---|---|---|---|---|---|---|---|
| | % | % | % | % | % | % | % | % | % |
| 1 | 0·08 | — | 0·03 | 0·02 | 0·02 | 0·03 | 0·02 | 99·80 | 0·12 |
| 1½ | 0·21 | — | 0·05 | 0·05 | 0·02 | 0·03 | 0·02 | 99·62 | 0·17 |
| 2 | 0·38 | — | 0·03 | 0·08 | 0·02 | 0·02 | 0·03 | 99·44 | 0·18 |
| 3 | 0·59 | — | 0·07 | 0·10 | 0·02 | 0·02 | 0·03 | 99·17 | 0·24 |
| 3½ | 0·74 | — | 0·05 | 0·01 | 0·02 | 0·02 | 0·02 | 99·14 | 0·12 |
| 4 | 0·89 | — | 0·03 | 0·09 | 0·02 | 0·02 | 0·03 | 98·92 | 0·19 |
| 5 | 1·20 | 0·28 | 0·07 | 0·15 | 0·02 | 0·02 | 0·03 | 98·51 | 0·29 |
| 6 | 1·47 | 1·14 | 0·08 | 0·13 | 0·02 | 0·01 | 0·04 | 98·25 | 0·28 |

about 0·25%. The specimens therefore represented a set of practically pure carbon-iron alloys, that is, there was no other element present to mask in any way the effect of the carbon.

This work of Arnold's constituted a model of correlated research, that is the observations were not confined to one or two lines of investigation on materials of unsystematic composition. The information determined included chemical analysis, mechanical, physical and magnetic properties, micro-structure, thermal change points, the heat evolved on tempering and hardening steels, and other information. The results obtained from these different methods of investigation were compared carefully before conclusions were drawn. The analyses of the steels used are given in Table XV.

The results of the tensile tests on these carbon steels in the normalized condition are shown in Table XVI, and the tensile tests on bars in the annealed condition are given in Table XVII. The latter results are plotted in Fig. 39. The tenacity reaches a maximum at 0·89% of carbon, i.e. the eutectic composition. It subsequently falls owing to the separation of graphite by slow or prolonged cooling. The ductility is also at a minimum at the above composition.

The results of the compression tests on the annealed and also the hard steels are shown in Fig. 40. Here again the eutectic steel is critical, possessing the highest compression strength of the steels in the annealed condition and marking the point at which molecular flow ceases in the hardened steels. These breaks in the mechanical properties at 0·89% of carbon are reflected in micro-structure, also in the thermal and magnetic curves. In the microscopic examination of the hardened steels, attention is drawn to the practically homogeneous nature of the saturated or eutectic steel.

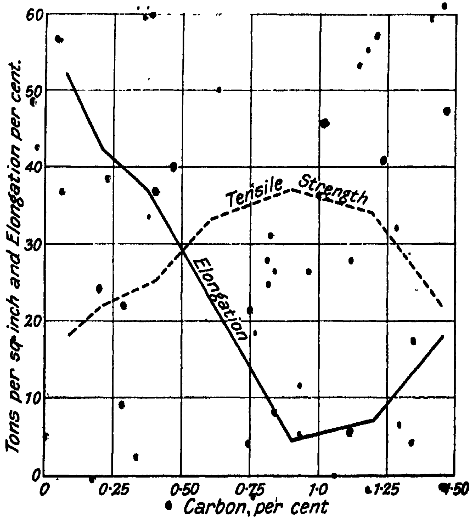

FIG. 39.—TENSILE STRENGTH AND ELONGATION OF ANNEALED CARBON STEEL.

(*J. O. Arnold, Proc. Inst.C.E.*, 1896.)

In the physical tests it is shown that the evolution of heat at the carbon change point increases approximately linearly with the carbon content up to 0·89% carbon steel, above which the heat evolution again decreases.

In investigating the magnetic properties of

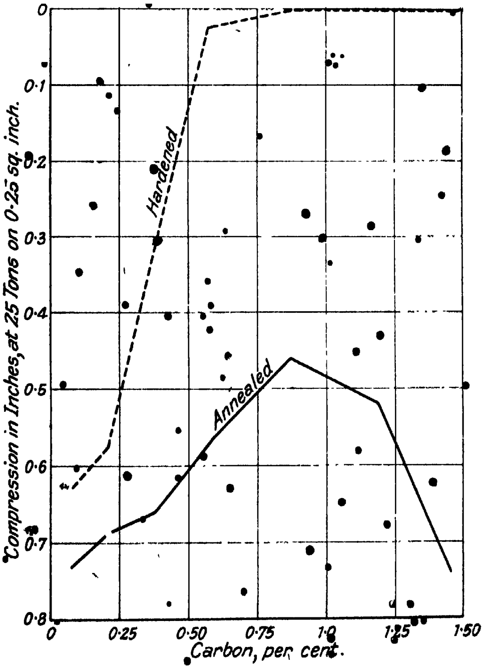

FIG. 40.—COMPRESSION TESTS ON HARDENED AND ANNEALED CARBON STEELS.

(*J. O. Arnold, Proc. Inst.C.E.*, 1896)

hardened carbon steels, Arnold showed that the magnetic permeability of these steels varied inversely as the percentage of carbon present, also that the permanent magnetism was directly proportional to the carbides of iron present. The curve of permanent magnetism increased linearly up to a composition of 0·89% of carbon, remaining constant when the carbon was increased above this amount. The sharp break at the above percentage is identical with that observed in the thermal and several of the mechanical curves, and corresponds with the microscopic saturation point. Attention is further drawn to the suitability of this 0·89% carbon steel for cutting tools which must be tough enough to withstand a certain shock, as for example in cold setts. If tools contain a higher percentage of carbon than the above, they are liable to crack owing to the lines of weakness formed by the surplus carbide present.

It may be mentioned that correct heat treatment of carbon steel makes proportionately quite as great a difference in the mechanical qualities, in fact much more so than is usually known. For many purposes the use of the more expensive alloy steel can be avoided if adequate care and skill are devoted to the simpler and less expensive material.

T. Simidu, of the Tohoku Imperial University, has shown that the electric resistance of carbon steels increases with carbon percentage from 0·14% to 1·50%, and that the thermal conductivity of carbon steels varies in the same manner as the electric conductivity.

Carbon steels are used for a large variety of small tools, but, as mentioned in Chapter XI, they have been largely superseded in cutting tools by high

## TABLE XVI

### TENSILE TESTS ON NORMALIZED BARS OF CARBON STEEL

Test-pieces 2 in. parallel by 0·564 in. diameter

| Steel No. | Carbon. | Elastic Limit. | Maximum Stress. | Elongation. | Reduction of Area. | Fracture. |
|---|---|---|---|---|---|---|
| | % | Tons per sq. in. | Tons per per sq. in. | % | % | |
| 1 | 0·08 | 12·19 | 21·39 | 46·6 | 74·8 | Grey granular silky edges |
| 1½ | 0·21 | 17·08 | 25·39 | 42·1 | 67·8 | ,, ,, |
| 2 | 0·38 | 17·95 | 29·94 | 34·5 | 56·5 | ,, ,, |
| 3 | 0·59 | 19·82 | 42·82 | 19·9 | 22·7 | Crystalline |
| 4 | 0·89 | 24·80 | 52·40 | 13·0 | 15·4 | ,, |
| 5 | 1·20 | 35·72 | 61·65 | 8·0 | 7·8 | ,, |
| 6 | 1·47 | 32·27 | 55·71 | 2·8 | 3·3 | ,, |

## TABLE XVII

### TENSILE TESTS ON ANNEALED BARS OF CARBON STEEL

Test pieces 2 in. parallel by 0·564 in. diameter

| Steel No. | Carbon. | Elastic Limit. | Maximum Stress. | Elongation. | Reduction of Area. | Fracture. |
|---|---|---|---|---|---|---|
| | % | Tons per sq. in. | Tons per sq. in. | % | % | |
| 1 | 0·08 | 8·82 | 18·34 | 52·7 | 76·7 | Grey granular silky edges |
| 1½ | 0·21 | 9·02 | 21·25 | 42·3 | 65·7 | ,, ,, |
| 2 | 0·38 | 9·55 | 25·02 | 35·0 | 50·6 | ,, ,, |
| 3 | 0·59 | 11·36 | 31·87 | 22·0 | [illegible]3·3 | Crystalline |
| 4 | 0·89 | 16·81 | 36·69 | 4·5 | 4·2 | ,, |
| 5 | 1·20 | 16·19 | 32·87 | 6·0 | 4·9 | ,, |
| 6 | 1·47 | 10·08 | 22·33 | 19·0 | 17·7 | Dark grey fibrous |

speed steels. Carbon steel containing 1% has been used for pens, but it is probable that it will be superseded in this application by steel of the rustless variety. In Austria carbon steel has been used satisfactorily for bridge work, competing with nickel steel in this connection.

An important application of carbon steel is in the manufacture of mining drills. In drill steel the carbon is usually about 0·8%, but decreases somewhat with smaller section. If the carbon steel is carefully made and correctly heat-treated, excellent results are obtained, which so far have not been exceeded by the addition of special alloying elements to the steel. The stresses on a drill are of a rather complex nature, but probably the most important is a repeated compression combined with a certain amount of bending and torsion; under these severe conditions, carbon steel has hitherto proved the best, even against the hardest and toughest rocks.

# APPENDIX II

## CLASSIFIED LIST OF PAPERS

by

SIR ROBERT A. HADFIELD, Bt., F.R.S.

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## SUMMARY

*Section*

(1) Manganese steel.
(2) Alloys of iron with silicon, aluminium, chromium, nickel, tungsten, copper, cobalt, molybdenum, and other elements.
(3) Sound steel.
(4) Mechanical tests.
(5) Hardness and hardening.
(6) Electrical and magnetic properties.
(7) Production of magnetic alloys from non-magnetic materials.
(8) Corrosion of iron and steel.
(9) Effect of low temperatures upon iron, steel, and alloy steels.
(10) Metallography.
(11) Pyrometers.
(12) X-ray examination of iron, steel, and other materials.
(13) Early history of crucible steel.
(14) Ancient iron and steel.
(15) Fuel.
(16) Addresses, presidential.
(17) Addresses, other than presidential.
(18) Progress of metallurgy.
(19) Contributions to discussions.
(20) Education.
(21) General.

## (1) MANGANESE STEEL

| No. | Title. | Where read or published. | Year. |
|---|---|---|---|
| 1 | Manganese Steel | Institution of Civil Engineers | 1888 |
| 2 | Some Newly-discovered Properties of Alloys of Iron and Manganese | Institution of Civil Engineers | 1888 |
| 3 | Manganese Steel | Iron and Steel Institute | 1888 |
| 9 | Iron Alloys, with special reference to Manganese Steel | American Institute of Mining Engineers | 1893 |
| 13 | The Results of Heat Treatment on Manganese Steel and their Bearing upon Carbon Steel | Iron and Steel Institute | 1894 |
| 15 | Steel and Iron Alloys | Institution of Civil Engineers | 1897 |
| 24 | Alloys of Iron, Manganese and Nickel | Institution of Civil Engineers | 1903 |
| 26 | Iron and Steel Alloys | *Iron and Steel Metallurgist and Metallographist* | 1904 |
| 31 | Seventh Report of the Alloys Research Committee on "The Properties of a Series of Iron-Nickel-Manganese Carbon Alloys"* | Institution of Mechanical Engineers | 1905 |
| 58 | Heating and Cooling Curves of Manganese Steel | Iron and Steel Institute | 1913 |
| 60 | Research with regard to the Non-Magnetic and Magnetic Conditions of Manganese Steel | American Institute of Mining Engineers | 1914 |
| 61 | Manganese Steel Rails | American Institute of Mining Engineers | 1914 |
| [illegible]4 | The Magnetic and Mechanical Properties of Manganese Steel* | Iron and Steel Institute | 1914 |
| 99 | A Contribution to the Study of the Magnetic Properties of Manganese, and of some special Manganese Steels* | Royal Society | 1917 |
| 126 | The Magnetic Mechanical Analysis of Manganese Steel* | Royal Society | 1920 |
| 128 | On the Influence of Low Temperatures on the Magnetic Properties of Alloys of Iron with Nickel and Manganese* | Royal Society | 1921 |

Joint paper with others.

## MANGANESE STEEL—(Contd.)

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 129 | On the Influence of Low Temperatures on the Magnetic Properties of Alloys of Iron with Nickel and Manganese* | Physical Laboratory of the University of Leiden | 1921 |

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* Joint paper with others.

## (2) ALLOYS OF IRON AND STEEL

### (Other than Manganese)

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 4 | Alloys of Iron and Silicon | Iron and Steel Institute | 1889 |
| 5 | Alloys of Iron and Silicon | British Association | 1889 |
| 6 | Alloys of Iron and Aluminium | Iron and Steel Institute | 1890 |
| 7 | Alloys of Iron and Chromium | Iron and Steel Institute | 1892 |
| 8 | Iron Alloys, with special reference to Manganese Steel | American Institute of Mining Engineers | 1893 |
| 15 | Steel and Iron Alloys | Institution of Civil Engineers | 1897 |
| 17 | Alloys of Iron & Nickel | Institution of Civil Engineers | 1899 |
| 24 | Alloys of Iron Manganese and Nickel | Institution of Civil Engineers | 1903 |
| 25 | Alloys of Iron & Tungsten | Iron and Steel Institute | 1903 |
| 26 | Iron and Steel Alloys, including<br>Iron and Cobalt<br>Iron and Copper<br>Iron and Titanium<br>Iron and Molybdenum<br>Iron and Vanadium | *Iron and Steel Metallurgist and Metallographist* | 1904 |
| 27 | Alloys of Iron (Researches on the Physical Properties of an Extensive Series)* | Royal Dublin Society | 1904 |
| 31 | On the Properties of a Series of Iron-Nickel-Manganese-Carbon Alloys.* (Seventh Report of the Alloys Research Committee) | Institution of Mechanical Engineers | 1905 |
| 70 | The Chemical and Mechanical Relations of Iron, Cobalt, and Carbon | Institution of Mechanical Engineers | 1915 |
| 76 | Alloys of Iron and Molybdenum | Institution of Mechanical Engineers | 1915 |

* Joint paper with others.

## (3) SOUND STEEL

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 41 | Expériences sur la Ségrégation dans les Lingots d'Acier | *Revue de Métallurgie* | 1910 |
| 51 | The Production of Sound Steel | *Iron Age* | 1912 |
| 53 | On a New Method of Revealing Segregation in Steel Ingots | Iron and Steel Institute | 1912 |
| 54 | Method of Producing Sound Ingots | Iron and Steel Institute | 1912 |
| 55 | Plant for Producing Sound Steel Ingots | American Institute of Mining Engineers | 1913 |
| 56 | Méthode pour produire des Lingots d'Acier Sains et Décéler la Ségrégation dans les Lingots d'Acier | *Revue de Métallurgie* | 1913 |
| 57 | Nouvelle Méthode pour Décéler la Ségrégation dans les Lingots d'Acie | *Revue de Métallurgie* | 1913 |
| 63 | Sound Ingots | American Institute of Mining Engineers | 1914 |
| 67 | Sound Steel Ingots and Rails* | American Institute of Mining Engineers | 1915 |
| 68 | Sound Steel for Rails and Structural Purposes | Franklin Institute | 1915 |
| 72 | Sound Steel Ingots and Rails* | Iron and Steel Institute | 1915 |
| 73 | Sound Steel for Rails and Structural Purposes. (Second Communication) | Franklin Institute | 1915 |

Joint paper with others.

## (4) MECHANICAL TESTS

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 98 | Impact Tests on Steel | Steel Treating Research Club | 1917 |
| 113 | Brinell and Scratch Tests for Steel* | Institution of Mechanical Engineers | 1919 |
| 127 | Shock Tests and Their Standardization* | Institution of Civil Engineers | 1920 |

* Joint paper with others.

## (5) HARDNESS AND HARDENING

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 40 | A Research on the Hardening of Carbon and Low Tungsten Tool Steels* | Institution of Mechanical Engineers | 1910 |
| 66 | Address as Chairman at discussion on "The Hardening of Metals"* | Faraday Society | 1914 |
| 90 | Contribution to Discussion on Hardness Tests Research Committee Report | Institution of Mechanical Engineers | 1916 |
| 94 | Spontaneous Generation of Heat in Recently Hardened Steel* | Royal Society | 1917 |
| 103 | Further Experiments on the Spontaneous Generation of Heat in Recently Hardened Steel* | Faraday Society | 1918 |
| 105 | Contribution on Hardness | Institution of Mechanical Engineers | 1918 |
| 113 | Brinell and Scratch Tests for Steel* | Institution of Mechanical Engineers | 1919 |
| 127 | Shock Tests and Their Standardization* | Institution of Civil Engineers | 1920 |

* Joint paper with others.

## (6) ELECTRICAL AND MAGNETIC PROPERTIES

| No. | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 21 | On the Electrical Conductivity and Magnetic Permeability of Iron* | Royal Dublin Society | 1900 |
| 22 | Researches on the Electrical Conductivity and Magnetic Properties of upwards of One Hundred Different Alloys of Iron* | Institution of Electrical Engineers | 1902 |
| 23 | On the Magnetic Properties of an Extensive Series of Alloys of Iron* | Royal Dublin Society | 1902 |
| 32 | On the Magnetic Qualities of Some Alloys not Containing Iron* | Royal Society | 1905 |
| 39 | The Magnetic Properties of Iron and Its Alloys in Intense Fields* | Institution of Electrical Engineers | 1910 |
| 49 | The Magnetic Properties of Alloys. (Contribution to the International Discussion) | Faraday Society | 1912 |
| 60 | Research with Regard to the Non-Magnetic and Magnetic Conditions of Manganese Steel* | American Institute of Mining Engineers | 1914 |
| 64 | The Magnetic and Mechanical Properties of Manganese Steel* | Iron and Steel Institute | 1914 |
| 92 | The Corrosion and Electrical Properties of Steels* | Royal Society | 1916 |
| 99 | A Contribution to the Study of the Magnetic Properties of Manganese, and of Some Special Manganese Steels* | Royal Society | 1917 |
| 126 | The Magnetic Mechanical Analysis of Manganese Steel* | Royal Society | 1920 |
| 128 | On the Influence of Low Temperatures on the Magnetic Properties of Alloys of Iron with Nickel and Manganese* | Royal Society | 1921 |

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* Joint paper with others.

### (7) PRODUCTION OF MAGNETIC ALLOYS FROM NON-MAGNETIC METALS

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 28 | Magnetic Alloys from Non-Magnetic Metals | British Association | 1904 |
| 29 | Production of Magnetic Alloys from Non-Magnetic Metals | *Chemical News* | 1904 |

### (8) CORROSION OF IRON AND STEEL

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 77 | Address as President, entitled "Corrosion of Steel Alloys," at Discussion on "Corrosion of Metals" | Faraday Society | 1915 |
| 82 | The Influence of Carbon and Manganese upon the Corrosion of Iron and Steel* | Iron and Steel Institute | 1916 |
| 92 | The Corrosion and Electrical Properties of Steels* | Royal Society | 1916 |
| 133 | Corrosion of Ferrous Metals | Institution of Civil Engineers | 1922 |
| 135 | Corrosion of Iron and Steel | Royal Society | 1922 |

* Joint paper with others.

## (9) THE EFFECT OF LOW TEMPERATURES UPON IRON, STEEL, AND ALLOY STEELS

| No. | Title. | Where read or published. | Year. |
|---|---|---|---|
| 30 | On the Effect of Liquid Air Temperatures on the Mechanical and Other Properties of Iron and its Alloys* | Royal Society | 1904 |
| 34 | Experiments Relating to the Effect on Mechanical and Other Properties of Iron and its Alloys Produced by Liquid Air Temperatures | Iron and Steel Institute | 1905 |
| 35 | Effet de la Température de l'Air liquide sur les Propriétés mécaniques et autres du Fer et de ses Alliages | Congrès International des Mines, de la Métallurgie, de la Mécanique et de la Géologie Appliquées. (Section de Métallurgie) | 1905 |
| 128 | On the Influence of Low Temperatures on the Magnetic Properties of Alloys of Iron with Nickel and Manganese* | Royal Society | 1921 |
| 129 | On the Influence of Low Temperatures on the Magnetic Properties of Alloys of Iron with Nickel and Manganese* | Physical Laboratory of the University of Leiden | 1921 |

* Joint paper with others.

## (10) METALLOGRAPHY

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 116 | Address as President at General Discussion on "The Microscope" | Faraday Society | 1920 |
| 117 | Photomicrographs of Steel and Iron Sections at High Magnification* | Faraday Society | 1920 |
| 119 | The Great Works of Sorby | Faraday Society | 1920 |

* Joint paper with others.

## (11) PYROMETERS

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 71 | Address as Chairman at Discussion on Mr. Chas. R. Darling's Paper, "Recent Progress in Pyrometry" | Royal Society of Arts | 1915 |
| 100 | Address at General Discussion on "Pyrometers and Pyrometry" | Faraday Society | 1917 |

## (12) X-RAY EXAMINATION OF IRON, STEEL, AND OTHER MATERIALS

| No. | Title. | Where read or published. | Year. |
|---|---|---|---|
| 109 | Address as President at General Discussion on the Examination of Materials by X-Rays | Faraday Society and Röntgen Society | 1919 |
| 110 | Testing the Absorption Power of Different Steels under X-Rays* | Faraday Society | 1919 |
| 111 | X-Ray Examination as Applied to the Metallurgy of Steel* | Faraday Society | 1919 |
| 112 | Radiographic Examination of Carbon Electrodes Used in Electric Steel-making Furnaces* | Faraday Society | 1919 |

* Joint paper with others.

## (13) EARLY HISTORY OF CRUCIBLE STEEL

| No. | Title. | Where read or published. | Year. |
|---|---|---|---|
| 10 | Huntsman, the Inventor of Crucible Steel | American Institute of Mining Engineers | 1893 |
| 12 | The Early History of Crucible Steel | Iron and Steel Institute | 1894 |

## (14) ANCIENT IRON AND STEEL*

| No. | Title. | Where read or published. | Year. |
|---|---|---|---|
| 44 | Sinhalese Iron and Steel of Ancient Origin | Royal Society | 1911 |
| 45 | Sinhalese Iron and Steel of Ancient Origin | Iron and Steel Institute | 1911 |
| 46 | Abstract from Paper on "Sinhalese Iron and Steel of Ancient Origin" | *Nature* | 1912 |
| 47 | Abstract from Paper on "Sinhalese Iron and Steel of Ancient Origin," with Addendum regarding Delhi Pillar | Royal Society | 1912 |
| 48 | Analysis of the Iron Pillar, made about A.D. 300 at Delhi | *Engineering* | 1912 |

## (15) FUEL

| No. | Title. | Where read or published. | Year. |
|---|---|---|---|
| 101 | Presidential Address | Society of British Gas Industries | 1918 |
| 114 | Report on Fuel Economy and Consumption in the Manufacture of Iron and Steel* | Iron and Steel Institute | 1919 |
| 115 | Fuel Control in Metallurgical Furnaces* | Iron and Steel Institute | 1919 |
| 120 | Address as Chairman at Mr. H. M. Thornton's Lecture on "Gas in Relation to Industrial Production" | Royal Society of Arts | 1920 |

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* Joint paper with others.

## (16) ADDRESSES—PRESIDENTIAL

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 11 | Presidential Address | Sheffield Society of Metallurgists and Engineers | 1893 |
| 33 | Presidential Address | Iron and Steel Institute | 1905 |
| 37 | Presidential Address | Iron and Steel Institute: Joint Meeting with American Institute of Mining Engineers | 1906 |
| 65 | Presidential Address: ("Advances in the Metallurgy of Iron and Steel") | Faraday Society | 1914 |
| 01 | Presidential Address | Society of British Gas Industries | 1918 |
| 102 | Presidential Address to Society of British Gas Industries | *Gas* | 1918 |
| 124 | Presidential Address | British Commercial Gas Association | 1920 |

## (17) ADDRESSES—OTHER THAN PRESIDENTIAL

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 19 | Address as Master Cutler to the Cutlers' Co. | Sheffield Press | 1899 |
| 20 | Address and Distribution of Prizes to Students at Technical Dept. of Sheffield University College | Sheffield Press | 1899 |
| 36 | "James Forrest" Lecture on "Unsolved Problems in Metallurgy" | Institution of Civil Engineers | 1906 |
| 38 | Address to Students at Columbia University, New York | *Iron Age* | 1907 |
| 43 | Address at Sheffield University on the Conferment of Honorary Degree of Doctor of Metallurgy | Sheffield Press | 1911 |
| 59 | The Progress of the Metallurgy of Iron and Steel | American Institute of Mining Engineers | 1914 |
| 69 | History of the Metallurgy of Iron and Steel | Institution of Mechanical Engineers | 1915 |
| 71 | Address as Chairman at Discussion on Mr. Chas. R. Darling's Paper, "Recent Progress in Pyrometry" | Royal Society of Arts | 1915 |
| 74 | Address as Chairman at Discussion on "The Transformations of Iron" | Faraday Society | 1915 |
| 77 | Address as President, entitled "Corrosion of Steel Alloys" at Discussion on "Corrosion of Metals" | Faraday Society | 1915 |
| 80 | Address as Chairman at Discussion on "Methods and Appliances for the Attainment of High Temperatures in the Laboratory" | Faraday Society | 1916 |
| 81 | Address as Chairman at Dr. Rosenhain's Lecture on "The Making of a Big Gun" | Faraday Society | 1916 |
| 83 | Address as Chairman at Annual Banquet of London Association of Foremen Engineers | *The Managing Engineer* | 1916 |

## (17) ADDRESSES—OTHER THAN PRESIDENTIAL (contd.)

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 84 | Address as Chairman of Ferrous Section of Special Committee of Advisory Council | Board of Education | 1916 |
| 87 | Address as Chairman at Discussion on "Refractories" | Faraday Society | 1916 |
| 95 | Address as Chairman at Discussion on "The Training and Work of the Engineering Chemist" | Faraday Society | 1917 |
| 104 | Address as Chairman at General Discussion on "The Co-ordination of Scientific Publication" | Faraday Society | 1918 |
| 106 | Address as Chairman at General Discussion on "The Occlusion of Gases by Metals" | Faraday Society | 1918 |
| 107 | Address as Chairman at General Bagnall Wild's Lecture on "Aircraft Steels" | Royal Aeronautical Society | 1918 |
| 108 | Address as Chairman at General Discussion on "Electric Welding" | Royal Society of Arts | 1919 |
| 109 | Address as President at General Discussion on "The Examination of Materials by X-Rays" | Faraday Society and Röntgen Society | 1919 |
| 116 | Address as President at General Discussion on "The Microscope" | Faraday Society | 1920 |
| 118 | The Work of the Faraday Society, and Michael Faraday | Faraday Society | 1920 |
| 120 | Address as Chairman at Mr. H. M. Thornton's Lecture on "Gas in Relation to Industrial Production" | Royal Society of Arts | 1920 |
| 121 | Address as Chairman at General Discussion on "Basic Slags" | Faraday Society | 1920 |
| 122 | Address on the Work of the Nitrogen Products Committee | Faraday Society | 1920 |
| 123 | Address at Mr. M. S. Birkett's Lecture on "The Iron and Steel Trades During War" | Royal Statistical Society | 1920 |

## (17) ADDRESSES—OTHER THAN PRESIDENTIAL—(contd.)

| No. | Title. | Where read or published. | Year. |
|---|---|---|---|
| 125 | Address as Chairman at General Discussion on "Physics and Chemistry of Colloids and Their Bearing on Industrial Questions" | Faraday Society | 1920 |
| 130 | Address of Thanks on the occasion of the Award of the John Fritz Medal | Institution of Civil Engineers | 1921 |
| 131 | Address at Engineering Conference as Chairman of Section IV, "Mining and Metallurgy" | Institution of Civil Engineers | 1921 |
| 132 | The Work and Position of the Metallurgical Chemist | Sheffield Association of Metallurgists and Metallurgical Chemists | 1921 |
| 134 | Metallurgy of Iron and Steel | Pitman's Technical Primer Series | 1922 |

## (18) PROGRESS OF METALLURGY

| No. | Title. | Where read or published. | Year. |
|---|---|---|---|
| 42 | Les Progrès de la Métallurgie | *Le Génie Civil* | 1910 |
| 50 | The World's Progress in Metallurgy | *Iron Age* | 1912 |

## (19) SOME OF THE CONTRIBUTIONS TO DISCUSSIONS

| *No.* | *Title.* | *Where read or published.* | *Year.* |
|---|---|---|---|
| 62 | Contribution to Discussion on Mr. W. S. Potter's Paper on "Manganese Steel" | American Institute of Mining Engineers | 1914 |
| 70 | Contribution to Discussion on Dr. J. A. Arnold's Paper, "The Chemical and Mechanical Relations of Iron, Cobalt, and Carbon" | Institution of Mechanical Engineers | 1915 |
| 75 | Contribution to the Discussion of Dr. Dugald Clerk's Address, "English and German Methods Contrasted" | Royal Society of Arts | 1915 |
| 78 | Contribution to the Discussion on Dr. J. A. Fleming's Paper, "The Organization of Scientific Research" | Royal Society of Arts | 1918 |
| 79 | Contribution, "Britain's Part in the Trade War—Scientific Research" | *Daily Telegraph* (London) | 1916 |
| 95 | Contribution to Discussion on "The Mineral Resources of the British Empire" | Society of Engineers | 1916 |
| 96 | Contribution to Discussion on Sir Wm. Beardmore and Mr. H. H. Ashdown's Papers on "Heat Treatment of Steel Forgings" | Institution of Mechanical Engineers | 1917 |
| 97 | Contribution to Discussion on Mr. Edgar Crammond's Lecture, "Foreign Trade in Relation to the Investment of Capital Abroad" | Institution of Civil Engineers | 1917 |

## (20) EDUCATION

| No. | Title. | Where read or published. | Year. |
|---|---|---|---|
| 88 | Suggestions with Regard to the Co-ordination and Organization of Scientific and Technical Societies | Board of Scientific Societies | 1916 |
| 95 | Address as Chairman at Discussion on "The Training and Work of the Engineering Chemist" | Faraday Society | 1917 |

## (21) GENERAL

| No. | Title. | Where read or published. | Year. |
|---|---|---|---|
| 8 | Notes on the Chicago Exhibition | Iron and Steel Institute | 1893 |
| 14 | The Production of Iron by a New Process | Iron and Steel Institute | 1895 |
| 16 | Foreign Technical Progress | Iron and Steel Institute | 1897 |
| 18 | The Influence of Casting Temperature upon Steel | Institution of Civil Engineers | 1899 |
| 52 | The World's Production of Pig Iron | *The Times* | 1912 |
| 85 | Remarks to Sir Ray Lankester regarding "The Neglect of Science" | Report of Committee on "The Neglect of Science" | 1916 |
| 86 | The Training of Captains of Industry | *Iron and Coal Trades Review* | 1916 |
| 89 | Science and Trade | *Daily Telegraph* (London) | 1916 |
| 91 | Reply to *The New Age* Industrial Symposium Question | *The New Age* | 1916 |

# APPENDIX III

## LIST OF SYMPOSIA OF THE FARADAY SOCIETY

### (a) 1907–1914

| *No.* | *Date of Discussion.* | *Vol.* | *Title.* | *No. of Papers Read.* | *No. of Pages* |
|---|---|---|---|---|---|
| 1 | 1907, Jan. | III | Osmotic Pressure | 4 | 30 |
| 2 | 1907, June | III | Hydrates in Solution | 4 | 40 |
| 3 | 1910, April | VI | The Constitution of Water | 5 | 50 |
| 4 | 1911, May | VII | High Temperature Work | 5 | 40 |
| 5 | 1912, April | VIII | The Magnetic Properties of Alloys | 12 | 130 |
| 6 | 1913, Mar. | IX | Colloids and Their Viscosity | 5 | 80 |
| 7 | 1913, April | IX | The Corrosion of Iron and Steel (Manchester) | 4 | 30 |
| 8 | 1913, Nov. | IX | The Passivity of Metals | 8 | 90 |
| 9 | 1914, Mar. | X | Optical Rotatory Power | 11 | 100 |
| | | | | 58 | 590 |

### (b) DURING SIR ROBERT HADFIELD'S PRESIDENCY, 1914–1920

| | | | | | |
|---|---|---|---|---|---|
| 10 | 1914, Nov. | X | The Hardening of Metals | 10 | 100 |
| 11 | 1915, Oct. | XI | The Transformation of Pure Iron | 3 | 40 |
| 12 | 1915, Dec. | XI | The Corrosion of Metals | 8 | 120 |
| 13 | 1916, Mar. | XII | Methods and Appliances for the Attainment of High Temperatures in the Laboratory | 2 | 10 |
| 14 | 1916, Nov. | XII | Refractory Materials | 20 | 210 |
| 15 | 1917, Mar. | XIII | The Training and Work of the Chemical Engineer | 6 | 60 |
| 16 | 1917, May | XIII | Osmotic Pressure | 5 | 70 |
| 17 | 1917, Nov. | XIII | Pyrometers and Pyrometry | 1[illegible] | 180 |
| 18 | 1918, Jan. | XIV | The Setting of Cements and Plasters | 10 | 70 |
| 19 | 1918, Feb. | XIV | Electric Furnaces (Manc'st'r) | 3 | 50 |
| 20 | 1918, May | XIV | Co-ordination of Scientific Publication | 1 | 30 |
| 21 | 1918, Nov. | XIV | The Occlusion of Gases by Metals | 9 | 100 |
| 22 | 1919, Jan. | XV | The Present Position of the Theory of Ionization | 15 | 180 |

(*b*) 1914–1920 (*contd.*)

| *No.* | *Date of Discussion.* | *Vol.* | *Title.* | *No. of Papers Read.* | *No. of Pages.* |
|---|---|---|---|---|---|
| 23 | 1919, April | XV | Examination of Materials by X-Rays | 15 | 150 |
| 24 | 1920, Jan. | XVI | The Microscope | 50 | 260 |
| 25 | 1920, Mar. | XVI | Basic Slags | 10 | 50 |
| 26 | 1920, Oct. | XVI | Physics and Chemistry of Colloids and Their Bearing on Industrial Questions | 20 | 200 |
| | | | | 206 | 1880 |

(*c*) 1920–1922.

| | | | | | |
|---|---|---|---|---|---|
| 27 | 1920, Nov. | XVI | Electrodeposition and Electroplating | 12 | 67 |
| 28 | 1921, April | XVII | The Failure of Metals under Internal and Prolonged Stress | 20 | 220 |
| 29 | 1921, May | XVII | Physico-Chemical Problems relating to the Soil | 22 | 119 |
| 30 | 1921, Feb. | XVII | Capillarity | 5 | 23 |
| 31 | 1921, Sept. | XVII | Catalysis with Special Reference to Newer Theories of Chemical Action | 15 | 202 |
| 32 | 1922, Mar | XVIII | Some Properties of Powders | 10 | 60 |
| 33 | 1922, Oct. | | The Generation and Utilization of Cold | not | yet printed. |
| | | | | 84+ | 691 |

# APPENDIX IV

## TABLE XVIII

## COMPARATIVE TABLE

**Prepared by Sir ROBERT HADFIELD**

showing the relation between

**BRINELL BALL ALSO SCLEROSCOPE HARDNESS NUMBERS AND COMPRESSION STRENGTH, YIELD POINT, TENACITY, FREMONT AND IZOD SHOCK QUALITIES OF VARIOUS TYPES OF STEEL.**

This table represents the average of a large number of tests on all types of steel, and is intended as an approximate guide. Individual results must necessarily vary considerably from the average.

| Zones of Hardness: F to A | Approximate Scleroscope Hardness Number. | Brinell Ball Hardness Number. | Shock Qualities. | | | | | | Tensile Strength. | | | | Compression. On specimens 0·564" diam. and 0·70" in height. | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Average Fremont Test. | | | Average Izod Test. | Based on | Examples | Yield Point. | | Maximum Stress. | | Elastic Limit or 0·25% Compression | | Compression % (i.e. % shortening when 100 tons/sq. in. (= 163 kg./sq.mm.) is [illegible]) |
| | | | Kg.-metres. | Ft. lbs. | Angle of Bend in degs. | Ft. lbs. | | | Ton per sq. in. | Kgs. per sq. mm. | Ton per sq. in. | Kgs. per sq. mm. | Ton per sq. in. | Kgs. per sq. mm. | |
| F | 19<br>23<br>27<br>30<br>34 | 100<br>125<br>150<br>175<br>200 | 16<br><br>13 | 115<br>to<br>95 | 70°<br><br>50° | 80<br>to<br>55 | Carbon Steel | Forged mild and medium hard steel | 13<br>17<br>21<br>26<br>32 | 21<br>27<br>32<br>41<br>50 | 26<br>31<br>36<br>41<br>46 | 41<br>49<br>57<br>65<br>72 | 13<br>15<br>17<br>19<br>21 | 21<br>24<br>27<br>30<br>32 | 64·0<br>55·0<br>47·0<br>40·0<br>35·0 |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **E** | 38<br>42<br>46<br>50 | 225<br>250<br>275<br>300 | 13<br>7 | 95<br>to<br>51 | 50°<br>23° | 55<br>to<br>28 | Alloy steel, e.g. nickel chromium steel quenched and tempered | 50/60 ton alloy steel for bars, forgings, etc. | 38<br>44<br>50<br>55 | 60<br>69<br>79<br>87 | 51<br>56<br>[illegible]<br>64 | 80<br>88<br>95<br>101 | 23<br>26<br>30<br>34 | 36<br>41<br>47<br>54 | 31·0<br>27·0<br>23·0<br>19·0 |
| **D** | 54<br>57<br>61<br>64 | 325<br>350<br>375<br>400 | 7<br>3·5 | 51<br>to<br>25 | 23°<br>4° | 28<br>to<br>12 |  | 60/70 ton alloy steel for crankshaft 70/80 ton alloy steel for connecting rod forgings | 61<br>67<br>73<br>79 | 96<br>105<br>115<br>124 | 69<br>74<br>79<br>86 | 109<br>117<br>124<br>135 | 38<br>43<br>49<br>55 | 60<br>68<br>77<br>87 | 15·2<br>11·3<br>8·0<br>5·6 |
| **C** | 68<br>71<br>75<br>78 | 425<br>450<br>475<br>500 | 3·5<br>2·5 | 25<br>to<br>18 | 4°<br>2° | 12<br>to<br>8 |  | 100/120ton alloy steel for gears | 85<br>92<br>99<br>105 | 134<br>145<br>156<br>165 | 92<br>100<br>107<br>115 | 145<br>158<br>169<br>181 | 61<br>67<br>74<br>81 | 96<br>105<br>116<br>127 | 3·8<br>[illegible]<br>1·3<br>0·6 |
| **B** | 80<br>84<br>86<br>89 | 525<br>550<br>575<br>600 | 2·5<br>1·5 | 18<br>to<br>11 | 2°<br>1° | 8<br>to<br>4 |  | 120 ton alloy steel Dies for coldstamping, etc. | 111<br>118<br>125<br>132 | 175<br>186<br>197<br>208 | 122<br>130<br>137<br>145 | 192<br>205<br>216<br>228 | 87<br>94<br>101<br>108 | 137<br>148<br>159<br>170 | 0·23<br>0·21<br>0·20<br>0·18 |
| **A** | [illegible]<br>95<br>99<br>101 | 625*<br>650<br>675<br>700 | Below<br>1 | Below<br>7 | Below<br>1° | Below<br>3 | Carbon or alloy steel. | Hardened material of various types | 139<br>146<br>153<br>160 | 219<br>230<br>241<br>252 | 152<br>[illegible]<br>169<br>178 | 239<br>252<br>266<br>280 | 115<br>122<br>129<br>136 | 181<br>192<br>203<br>214 | 0·16<br>0·14<br>0·13<br>0·12 |
| **A 2**<br>Owing to want of data, but little is known about this extremely high zone of "super-hardness." | —<br>—<br>—<br>— | 725<br>750<br>775<br>800 | Not definitely determined |  |  |  | Carbon or alloy steel |  | Not definitely determined |  | Not definitely determined |  | 144<br>151<br>159<br>166 | 227<br>238<br>250<br>261 | 0·11<br>0·9<br>0·8<br>0·7 |

* Glass scratching hardness commences here.

The printed capital letters in the zone column refer to special sections of zones of hardness as follows—

| ZONE. | BRINELL BALL HARDNESS NUMBER. |  | SCLEROSCOPE HARDNESS NUMBER. |  | YIELD POINT. Tons per sq. inch. |  | MAXIMUM STRESS. Tons per sq. inch. |  |
|---|---|---|---|---|---|---|---|---|
|  | FROM | TO | FROM | TO | FROM | TO | FROM | TO |
| F | 100 | 199 | 19 | 34 | 13 | 32 | 26 | 46 |
| E | 200 | 299 | 34 | 50 | 32 | 55 | 46 | 64 |
| D | 300 | 399 | 50 | 64 | 55 | 79 | 64 | 86 |
| C | 400 | 499 | 64 | 78 | 79 | 105 | 86 | 115 |
| B | 500 | 599 | 78 | 89 | 105 | 132 | 115 | 145 |
| A | 600 | 699 | 89 | 101 | 132 | Not definitely determined | 145 | Not definitely determined |

CONVERSION TABLE of work required to fracture Nicked Frémont and Izod Specimens.

FT. LBS.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Frémont** | 4 | 7 | 14 | 22 | 29 | 36 | 43 | 50 | 58 | 65 | 72 | 108 | 145 | 180 | 217 |
| **Izod** | 2 | 4 | 8 | 12 | 16 | 20 | 24 | 28 | 32 | 36 | 40 | 59 | 78 | 95 | 110 |

RELATIVE HARDNESS OF MICROCONSTITUENTS OF CARBON STEEL.

Pure Iron or Ferrite . 1 Sorbite . . . 52
Troostite. . . . @ 88 Austenite . 104
Martensite . 259.

Based on scratch tests, and necessarily only approximate.

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*Elementary Metallurgy.* (New York, 1917.)
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*Metallography* [Vol. II] (New York, 1921.)

The undermentioned Technical Primers (Pitman, 2s. 6d. net) are likely to interest readers of the present volume—

*Metallurgy of Iron and Steel.* Based on Papers by Sir Robert Hadfield.
*The Electric Furnace,* by F. J. Moffett.
*Pyrometers and Pyrometry,* by Ezer Griffiths. (In preparation.)
*Foundrywork,* by Ben Shaw and James Edgar.
*Patternmaking,* by the same Authors.
*Electricity in Steel Works,* by W. Macfarlane.

*Industrial Motor Control (Direct Current)*, by A. T. Dover.
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*Industrial Applications of X-Rays*, by P. H. S. Kempton.
*Structural Steelwork*, by W. H. Black.
*Metal Cutting Tools and Speeds*, by W. G. Burley. (In preparation.)
*Tool and Machine Setting*, by Ph. Gates.
*Capstan and Automatic Lathes*, by the same Author.
*Abrasive Materials*, by A. B. Searle.
*Grinding Machines and Their Use*, by T. R. Shaw.

Many other volumes are in preparation for the Technical Primer Series, full particulars of which can be obtained from the publishers at Pitman House, Parker Street, Kingsway, W.C.2

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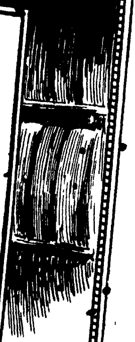

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